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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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Journal of Sedimentary Petrology

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NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal,* should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

Among papers to appear in forthcoming issues of the *Journal* are the following:

Recent history of a sand spit at San Nicolas Island, California. By Robert M. Norris.

Selenite crystals in the clays of Great Salt Lake. By A. J. Eardley and Bronson Stringham.

Feldspathized sandstone. By Robert R. Berg.

Study of the dispersing agents. By George Tchillingarian.

The origin of stylolites. By N. Prokopovich.

Imbrication and initial dip in a Keweenawan conglomerate bed. By Walter S. White.

Para-ripples in limestone, with special reference to occurrence in the Mississippian Boone formation. By V. O. Tansey.

An occurrence of artificial oolites. By J. B. Reark.

ERRATUM

Vol. 22, No. 2, p. 119, first column, line 41; for "serial factors" read "aerial factors."

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 22, NO. 3, PP. 125–145
FIGS. 1–9, SEPTEMBER, 1952

MEASURES FOR DESCRIBING THE SIZE DISTRIBUTION OF SEDIMENTS[1]

DOUGLAS L. INMAN

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ABSTRACT

Numerous measures are used in the literature to describe the grain-size distribution of sediments. Consideration of these measures indicates that parameters computed from quartiles may not be as significant as those based on more rigorous statistical concepts. In addition, the lack of standardization of descriptive measures has resulted in limited application of the findings from one locality to another.

The use of five parameters that serve as approximate graphic analogies to the moment measures commonly employed in statistics is recommended. The parameters are computed from five percentile diameters obtained from the cumulative size-frequency curve of a sediment. They include the mean (or median) diameter, standard deviation, kurtosis, and two measures of skewness, the second measure being sensitive to skew properties of the "tails" of the sediment distribution. If the five descriptive measures are listed for a sediment, it is possible to compute the five percentile diameters on which they are based (ϕ_5, ϕ_{16}, ϕ_{50}, ϕ_{84}, and ϕ_{95}), and hence five significant points on the cumulative curve of the sediment. This increases the value of the data listed for a sediment in a report, and in many cases eliminates the necessity of including the complete mechanical analysis of the sediment.

The degree of correlation of the graphic parameters to the corresponding moment measures decreases as the distribution becomes more skew. However, for a fairly wide range of distributions, the first three moment measures can be ascertained from the graphic parameters with about the same degree of accuracy as is obtained by computing rough moment measures.

INTRODUCTION

Numerous descriptive measures obtained from the grain-size analysis of sediments are used in the literature to indicate the salient features of the size-frequency distribution of a sediment. These measures range in complexity from those obtained by computing the various moments[2] of the sample distribution about some central measure of sediment diameter, to those obtained by selecting a few points from the cumulative frequency curve of the sediment. The latter include such measures as the Trask coefficients of sorting and skewness, and Kelley's quartile kurtosis.

One of the fundamental purposes in listing sediment parameters is to facilitate the comparison of sediment analyses and to aid in the correlation between sediment types and their environment. There may be special studies for which standardization of descriptive parameters is not warranted; however, in general the use of widely divergent systems has markedly lessened the value of many sediment studies. For example, a worker who wishes to compare his findings with those of other workers is virtually limited to those studies employing the same or comparable parameters. Also, the significance of some works has undoubtedly suffered from the use of parameters that are not truly "relevant."[3] Since the field of sedimentation is expanding rapidly, this may be an opportune time to briefly review procedures now in use and make suggestions for standardization of the descriptive measures to be used in sediment work.

[1] Contribution from the Scripps Institution of Oceanography, New Series No. 581. This work represents in part research carried out for the Beach Erosion Board and the Office of Naval Research under contract with the University of California.

[2] Discussion of moment measures is included in the appendix.

[3] Otto (1939) defines relevant parameters as numerical values which contain the essential information in a mechanical analysis.

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I wish to thank Dr. G. F. McEwen, Dr. F. P. Shepard, Dr. Roger Revelle, Dr. R. S. Arthur, and Mr. P. C. Scruton of Scripps Institution of Oceanography, Dr. W. C. Krumbein of Northwestern University, Dr. K. O. Emery and Mr. Howard Gould of the University of Southern California, and Dr. H. W. Menard, Jr., and Dr. R. S. Dietz of the Navy Electronics Laboratory, San Diego, California, for their helpful suggestions and critical readings of the manuscript. I am indebted to Dr. McEwen for furnishing the material for figure 2, and to D. B. Sayner, R. L. Fisher, Ruth Young, H. W. Blair, R. A. Mills, and Elizabeth Sanborn for helping with the illustrations and computations.

DISCUSSION OF DESCRIPTIVE PARAMETERS

The size-frequency distribution curves of sediments become more symmetrical when the logarithm of the diameter instead of the diameter is plotted as the independent variable. In many cases these curves approach normal distributions or one of the family of curves derived from a normal distribution.[4] This is of advantage because it allows the properties of the distribution to be described in terms of deviations or anomalies from the normal distribution, which is a procedure well-established in mathematical statistics. This advantage has long been recognized in other fields of study (Gaddum, 1945), and is utilized in the parameters recommended in this study. Since a logarithmic diameter has more significance in a discussion of the statistical relations of sediments, the phi notation of Krumbein (1936a), where $\phi = -\log_2$ of the diameter in millimeters, will be used in this paper. A conversion chart from millimeters to phi units is given in figure 1.

[4] A normal distribution is one whose frequency distribution curve is "bell-shaped," and symmetrical. A more complete description is given in the appendix.

Parameters such as the standard deviation, skewness, etc. obtained from moments may in most cases be the most significant or relevant numerical descriptions of size-frequency distributions because they are based on standard mathematical statistical relations and take into consideration the entire sediment distribution. On the other hand, the dependence of moment measures on the entire distribution is a limitation to their practical application to sediments, since mechanical analyses of sediments frequently result in open-ended curves, and thus do not give the coarse and fine limits of the distribution. Another disadvantage of moment measures is the complex and time-consuming procedure required to compute them. These facts have resulted in very limited use of these parameters in the description of sediments.

Quartile measures such as Trask's coefficients of sorting and skewness[5] and their equivalents in phi notation are easy to compute and hence have received rather wide usage. However, quartile measures are limited in value since they are based on the central 50 per cent of the sediment distribution. Significant differences in the upper or lower 25 per cent of a sample are not shown by quartile measurements. This inadequacy of quartile measurements to express the salient features of sediment distributions has been observed by many workers in sediments (for example, Doeglas, 1946). Also, measures of sorting based on quartiles have no particular significance in the geometry of a normal curve, whereas the standard deviation, which is the measure of dispersion or sorting most commonly used in statistics, gives the inflection points in a normal distribution. Krumbein (1936a) gives an excellent discussion of this subject.

[5] The sorting coefficient (Trask, 1932) is defined as $So = \sqrt{Q_1/Q_3}$, and the skewness coefficient as $Sk = Q_1Q_3/Md^2$, where Q_1 and Q_3 are the diameters in millimeters corresponding to the 25th and 75th percentiles respectively of a cumulative per cent (coarser) curve, and Md is the median diameter.

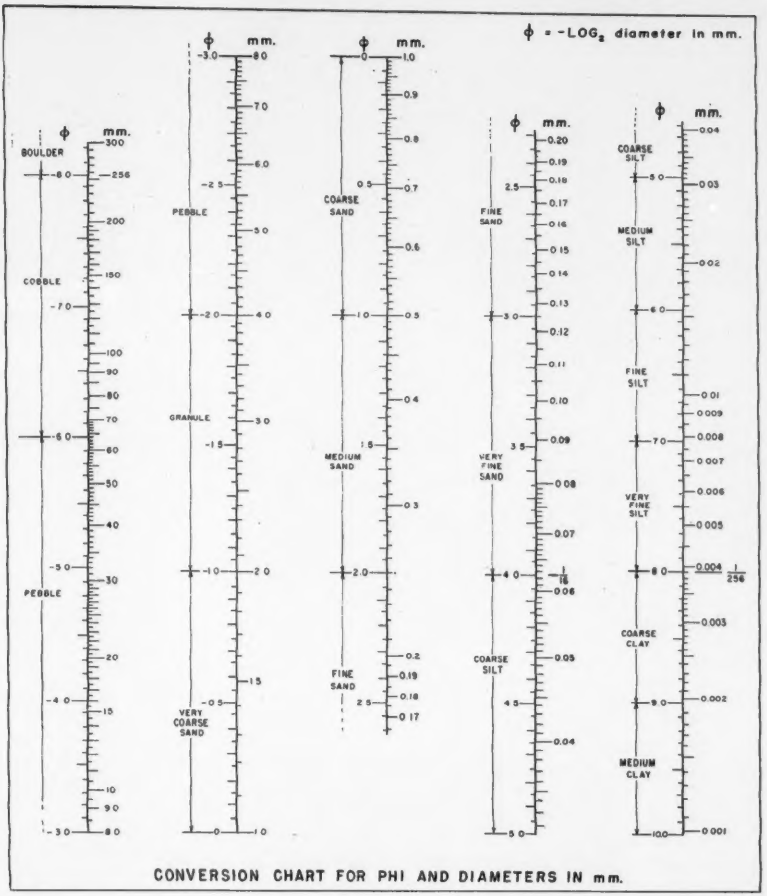


FIG. 1.

Quartile measurements in the millimeter notation have several other disadvantages. In the first place, Trask's sorting coefficient, *So*, is geometric rather than arithmetic, and thus does not lend itself to a visualization of the dispersion or sorting of the sediment. For example, a sediment whose sorting coefficient is 1.5 is not twice as well sorted as one having a value of 3.0. The dispersion of the second distribution is nearly 2.8 times greater than that of the distribution whose sorting is 1.5.

In addition, quartile skewness measures, either in millimeter or phi notation,[6] are dependent on the dispersion or

[6] Krumbein (1936b) defines a phi quartile skewness as $Skq_\phi = \frac{1}{2}(Q_{1\phi} + Q_{3\phi}) - Md\phi$ where $Q_{1\phi}$ and $Q_{3\phi}$ are the phi diameters corresponding to the 25th and 75th percentiles respec-

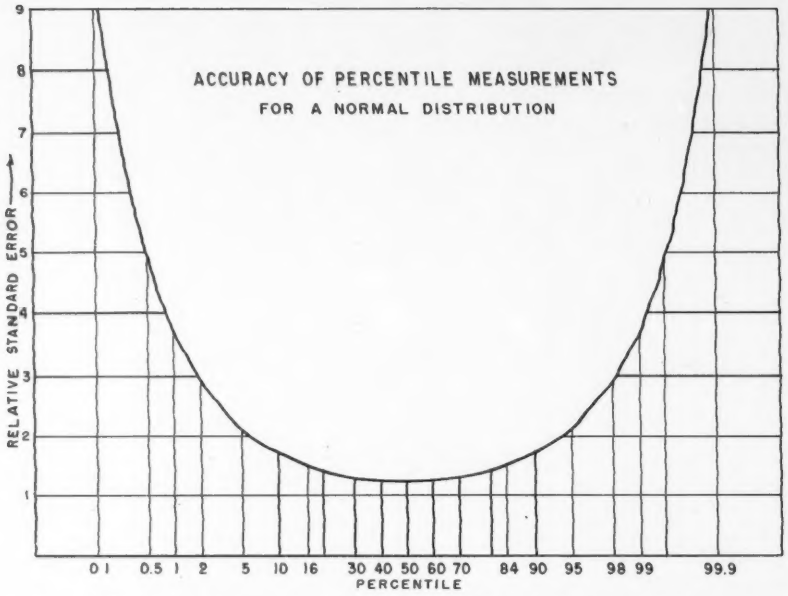


FIG. 2.—Showing the influence of fluctuations of sampling on the accuracy of various percentile measurements for a normal distribution. Note that errors are greatly increased for percentiles below 5 and above 95. (The ordinate of this curve is the relation $\sqrt{pq}/y_p$ which is derived in Yule and Kendall (1948), p. 382, equation 20.1. The true standard error for a given sample is the product of this quantity and $\sigma/\sqrt{n}$, where σ is the standard deviation of the sample, and n the number of observations.)

sorting of the sediment distribution. Thus distributions having the same value of quartile skewness coefficient do not have the same skewness values (as obtained by moment measures, for example) *unless* they have the same sorting. This will be discussed further in the section on measures of skewness.

Other measures such as Baker's (1920) equivalent grade and grading factor and Niggli's statistical parameters have also been widely used (see Krumbein and Pettijohn, 1938, pp. 255–257). A possible disadvantage of these measures is that it is necessary in computing them to use, for the independent variable, a diameter scale which is arithmetic in the millimeter notation. This scale results in pronounced skewness of the grain-size distribution which is reflected in the measures. For example, the measure of central tendency, the equivalent grade, is the arithmetic mean diameter in millimeters of the distribution, and because of this arithmetic character may not be as significant as a logarithmic measure of central tendency (Krumbein, 1936a, p. 37). In addition, the calculation of these parameters requires the use of a planimeter and is lengthy.

In a normal frequency distribution curve approximately 68 per cent of the population occurs between plus and minus one standard deviation to either side of the mean (or median, since these

tively of a cumulative per cent (coarser) curve and $Md\phi$ is the phi median diameter.

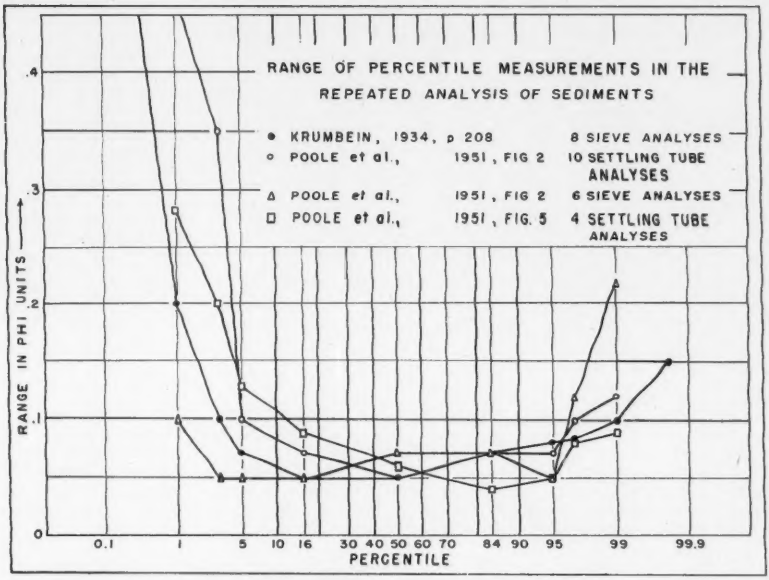

RANGE OF PERCENTILE MEASUREMENTS IN THE
REPEATED ANALYSIS OF SEDIMENTS
• KRUMBEIN, 1934, p 208 8 SIEVE ANALYSES
○ POOLE et al., 1951, FIG 2 10 SETTLING TUBE ANALYSES
△ POOLE et al., 1951, FIG 2 6 SIEVE ANALYSES
□ POOLE et al., 1951, FIG. 5 4 SETTLING TUBE ANALYSES
RANGE IN PHI UNITS
.4
.3
.2
.1
0
0.1 1 5 10 16 30 40 50 60 70 84 90 95 99 99.9
PERCENTILE

FIG. 3.—Range in phi units for various percentiles from the cumulative curves of repeated analyses of each of several samples. Note the wide range for percentiles less than 5 and greater than 95.

two measures are equal for a normal distribution), and 95 per cent occurs between two standard deviations either side of the mean. Thus the 16th and 84th percentiles of a normal sediment cumulative frequency curve represent diameters one standard deviation either side of the mean, and the $2\frac{1}{2}$ and $97\frac{1}{2}$ percentiles represent diameters two standard deviations either side of the mean.

Since many sediment distributions approximate a normal distribution or one of the family of curves derived from it, the use of percentiles based on standard deviations seems more meaningful for the description of size frequency distributions then those based on quartiles. However, before choosing definite percentiles for this description, the accuracy which can be obtained in the measurement of various percentiles in the size-distribution of sediments should be considered. From statistical theory it can be shown that the influence of fluctuations of sampling and analysis on percentiles increases away from the median (Yule and Kendall, 1948, p. 382). A curve showing the theoretical accuracy of percentile measurements for a normal distribution is shown in figure 2. The range in phi units for various percentiles from the cumulative curves of repeated analyses of each of several sediments is shown in figure 3. Inspection of these figures indicates that percentiles one standard deviation either side of the median (ϕ_{16} and ϕ_{84}) can be determined with almost the same accuracy as the median, and that there is appreciably greater inaccuracy in percentile measurements two standard deviations either side of the median ($\phi_{2\frac{1}{2}}$ and $\phi_{97\frac{1}{2}}$). However, the rerors in measuring the 5th and 95th percentiles are appreciably less than those

TABLE 1.—*Descriptive measures*

Measure		Nomenclature	Definition
Central Tendency	1*	Phi Median Diameter	$Md_\phi = \phi_{50}$ $= M_\phi - (\sigma_\phi \alpha_\phi)$
		Phi Mean Diameter	$M_\phi = \frac{1}{2}(\phi_{16} + \phi_{84})$ $= Md_\phi + (\sigma_\phi \alpha_\phi)$
Dispersion (Sorting)	2	Phi Deviation Measure	$\sigma_\phi = \frac{1}{2}(\phi_{84} - \phi_{16})$
Skewness	3	Phi Skewness Measure	$\alpha_\phi = \frac{M_\phi - Md_\phi}{\sigma_\phi}$
	4	2nd Phi Skewness Measure	$\alpha_{2\phi} = \frac{\frac{1}{2}(\phi_5 + \phi_{95}) - Md_\phi}{\sigma_\phi}$
Kurtosis (Peakedness)	5	Phi Kurtosis Measure	$\beta_\phi = \frac{\frac{1}{2}(\phi_{95} - \phi_5) - \sigma_\phi}{\sigma_\phi}$
Diameter in Phi Units corresponding to a given percentage		5th Percentile Diameter	$\phi_5 = Md_\phi - \sigma_\phi + \sigma_\phi(\alpha_{2\phi} - \beta_\phi)$
		16th Percentile Diameter	$\phi_{16} = Md_\phi - \sigma_\phi + (\sigma_\phi \alpha_\phi)$
		50th Percentile Diameter	$\phi_{50} = Md_\phi$
		84th Percentile Diameter	$\phi_{84} = Md_\phi + \sigma_\phi + (\sigma_\phi \alpha_\phi)$
		95th Percentile Diameter	$\phi_{95} = Md_\phi + \sigma_\phi + \sigma_\phi(\alpha_{2\phi} + \beta_\phi)$

* In reporting data, it is sufficient to list only one measure of central tendency, since the second may easily be computed from the other parameters.

for the $2\frac{1}{2}$ and $97\frac{1}{2}$ percentiles. Further, it would be extremely difficult to obtain the $97\frac{1}{2}$ percentile diameter in the analysis of many fine-grained sediments. For these reasons, the 5th and 95th percentile diameters, obtained from the cumulative frequency curve, as used in this study as a working approximation to two standard deviations from the mean.[7]

Since descriptive parameters based on moments are too time-consuming for extensive application to sediments, and parameters obtained from quartile measures do not take into consideration a sufficient proportion of the total sample (i.e., in many cases they may not be "relevant parameters"), the most suitable compromise would seem to be the selection of parameters based on a graphic analogy to moment measures. Otto (1939) was one of the first to apply this concept to sediment distributions when he devised his modified logarithmic probability graph. He utilized the 16th and 84th percentile diameters to obtain a standard deviation, and the 4th or 96th percentile in calculating a measure of skewness. His method requires a special type of graph paper and the skewness term is only based on one end of the distribution.

The considerations discussed above have led to the selection of five parameters to describe the frequency distribution of sediments. These descriptive measures are defined in table 1, and are illustrated graphically in figure 4. Also, a simplified sheet for their calculation is

[7] The 5th and 95th percentile diameters represent measurements 1.65 standard deviations either side of the mean in a normal distribution.

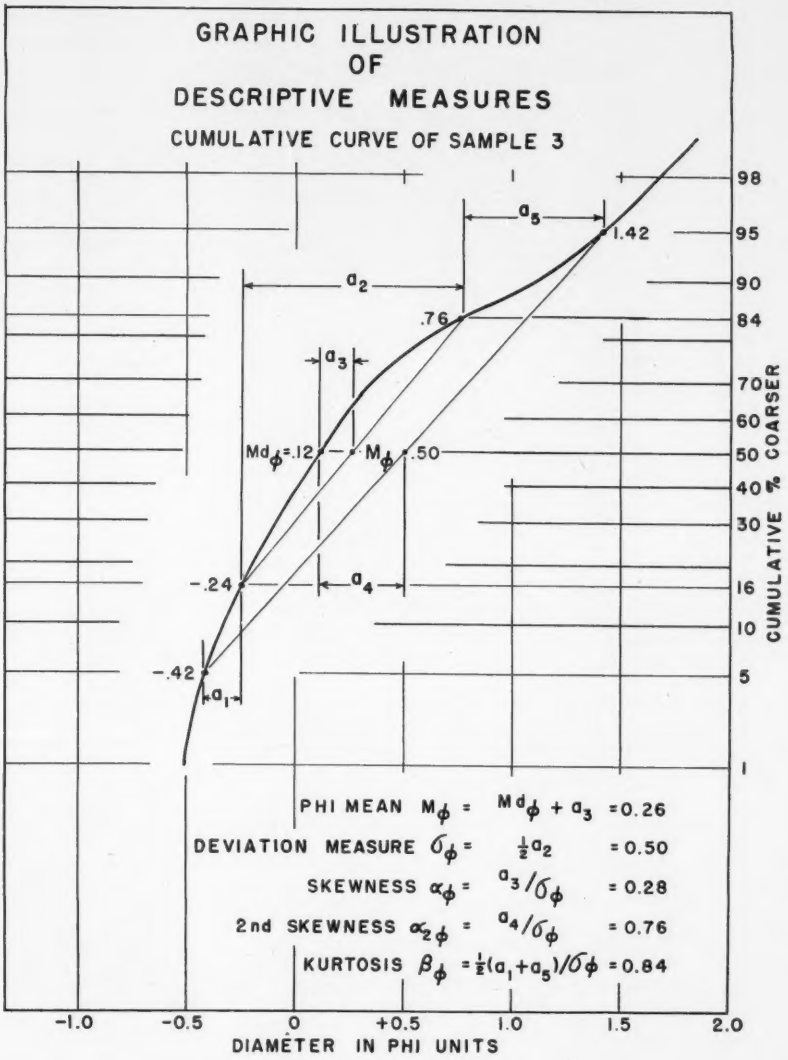


FIG. 4.

given in table 2, and a comparison of these parameters with those based on quartile measurements is given in table 3. The limits of accuracy, and the statistical basis of selection of the measures are discussed in the appendix. The measures

TABLE 2.—*Sample calculation sheet for the descriptive measures of sample 3*

Values of Md_ϕ, ϕ_{84}, ϕ_{16}, ϕ_{95} and ϕ_5 are obtained from the cumulative frequency curve shown in figure 4

Parameter notations are defined in table 1

$\phi_{84} = 0.76$	$Md_\phi = 0.12$
$\phi_{16} = -0.24$	
$\phi_{84} - \phi_{16} = 1.00\ (\frac{1}{2}) =$	$\sigma_\phi = 0.50$
$\phi_{84} + \phi_{16}\quad 0.52\ (\frac{1}{2}) =$	$M_\phi = 0.26$
$M_\phi - Md_\phi =$	$S = +0.14$
$S/\sigma_\phi =$	$\sigma_\phi = +0.28$
$\phi_{95} = 1.42$	
$\phi_5 = -0.42$	
$\phi_{95} - \phi_5 = 1.84\ (\frac{1}{2}) =$	$K = 0.92$
$K/\sigma_\phi - 1 =$	$\beta_\phi = 0.84$
$\phi_{95} + \phi_5 = 1.00\ (\frac{1}{2}) =$	$M_z = 0.50$
$M_z - Md_\phi =$	$S_z = 0.38$
$S_z/\sigma_\phi =$	$\alpha_{2\phi} = +0.76$

recommended in this study have been selected with the following points in mind:

1. The measures serve as approximate graphic equivalents to the moment measures commonly employed in statistics, and the notation is that generally used for analogous measures in statistics.
2. The parameters are based on five percentile diameters (ϕ_5, ϕ_{16}, ϕ_{50}, ϕ_{84}, and ϕ_{95}) obtained from a cumulative frequency curve of the sediment distribution. It is recommended that the cumulative curve be plotted on arithmetic probability paper (Hazen, 1914) since use of this paper results in a straight line plot for a normal distribution and thus facilitates curve fitting and visual interpretation of the data.
3. The measures are easy to visualize in terms of the sediment distribution (see figures 4 and 6), and are readily computed by subtraction and addition (see table 2).
4. Listing of the five measures gives the necessary data for computing five significant points on the cumulative frequency curve of the sediment (i.e., ϕ_5, ϕ_{16}, ϕ_{50}, ϕ_{84}, ϕ_{95}, see table 1) and thus in many cases will eliminate the necessity of reporting the complete mechanical analysis of the sediment.
5. It is recognized that some distributions may be adequately described by three parameters, a measure of central tendency, a measure of dispersion, and one of skewness. Also in some cases it may not be practical to measure percentile diameters as near the extremes of the distribution as the 5th and 95th percentile diameters. For these reasons the measures are selected so that distributions may be described by listing the three primary measures based on the 16th, 50th, and 84th percentile diameters. The primary parameters consist of a measure of central tendency (either the median or the mean), the phi deviation measure, σ_ϕ, and the phi skewness measure α_ϕ. These are somewhat similar in form to the phi quartile measures suggested by Krumbein (1936b), but have the advantage of being analogous to moment measures, and consider a larger percentage of the total distribution. However, whenever possible, five parameters should be listed, since they furnish a more complete description of the distribution.

Measures of Central Tendency—It is useful to be able to obtain both a median and a mean diameter since one may be more significant than the other for different studies. Both the phi median diameter, Md_ϕ, and the phi arithmetic mean

TABLE 3a.—*Comparison of descriptive measures in the phi notation based on approximate standard deviations with those based on quartile measurements*

Parameter	Sample Number			
	3	12	34	60
Phi Median Diameter, $Md_\phi = \phi_{50}$	0.12	2.25	3.78	3.28
Phi Mean Diameter, $M_\phi = \frac{1}{2}(\phi_{16} + \phi_{84})$	0.26	2.10	4.06	3.24
Phi Deviation Measure, $\sigma_\phi = \frac{1}{2}(\phi_{84} - \phi_{16})$	0.50	0.51	0.74	0.41
Phi Skewness Measure, $\alpha_\phi = \frac{M_\phi - Md_\phi}{\sigma_\phi}$	+0.28	−0.29	+0.38	−0.10
2nd Phi Skewness Measure, $\alpha_{2\phi} = \frac{\frac{1}{2}(\phi_5 + \phi_{95}) - Md_\phi}{\sigma_\phi}$	+0.76	−0.81	+0.97	−0.23
Phi Kurtosis Measure, $\beta_\phi = \frac{\frac{1}{2}(\phi_{95} - \phi_5) - \sigma_\phi}{\sigma_\phi}$	0.84	0.83	0.96	0.57
Skewness Ratio, $R_\phi = \alpha_{2\phi}/\alpha_\phi$	2.71	2.79	2.55	2.30
Phi Quartile Deviation,[1] $QD_\phi = \frac{1}{2}(Q_{3\phi} - Q_{1\phi})$	0.30	0.31	0.42	0.28
Phi Quartile Skewness,[1] $Skq_\phi = \frac{1}{2}(Q_{1\phi} + Q_{3\phi}) - Md_\phi$	+0.04	−0.07	+0.10	−0.01
Phi Quartile Kurtosis,[1] $K_{q\phi} = (Q_{3\phi} - Q_{1\phi})/2(P_{90\phi} - P_{10\phi})$	0.21	0.23	0.20	0.28

TABLE 3b.—*Descriptive parameters in the millimeter notation*[1]

Median Diameter, Md (mm)	0.92	0.21	0.073	0.103
Trask Sorting Coefficient, $So = \sqrt{Q_1/Q_3}$	1.23	1.23	1.34	1.22
Trask Skewness Coefficient, $Sk = \frac{Q_1 Q_3}{Md^2}$	0.96	1.08	0.88	0.01
Kelley's Quartile Kurtosis, $Kq_a = (Q_3 - Q_1)/2(_1P_{90} - P_{10})$	0.24	0.20	0.25	0.26

[1] Discussion of these parameters is given in Krumbein and Pettijohn (1938) pp. 230–238.

diameter, M_ϕ, may be obtained from the points selected from the cumulative frequency curve. They are defined as follows:

$$Md_\phi = \phi_{50} = M_\phi - (\sigma_\phi \alpha_\phi)$$

and

$$M_\phi = \tfrac{1}{2}(\phi_{16} + \phi_{84}) = Md_\phi + (\sigma_\phi \alpha_\phi).$$

The phi deviation measure σ_ϕ, and the phi skewness measure, α_ϕ, are defined in table 1 and will be discussed in a later section. It should be noted that it is necessary to list only one of these measures of central tendency in reporting the descriptive parameters of a grain-size distribution because the other may readily be computed from the remaining parameters.

The median diameter is the 50th percentile diameter of a cumulative frequency curve, and thus may be obtained directly from the curve without interpolation. The median is less affected by extreme values of skewness because it is closer to the modal diameter than the mean. Therefore, the median would be a more useful measure of central tendency than the mean where the emphasis is on the more abundant size. On the other hand, the arithmetic mean can be manipulated algebraically, so that the average of the means of several samples will give the mean of the group. For example, consider a sediment sample which is composed of numerous laminae of equal thickness but having different grain-size distributions. For such a sample, the mean grain-size of the total sample is equal to the average of the means of the laminae, whereas the

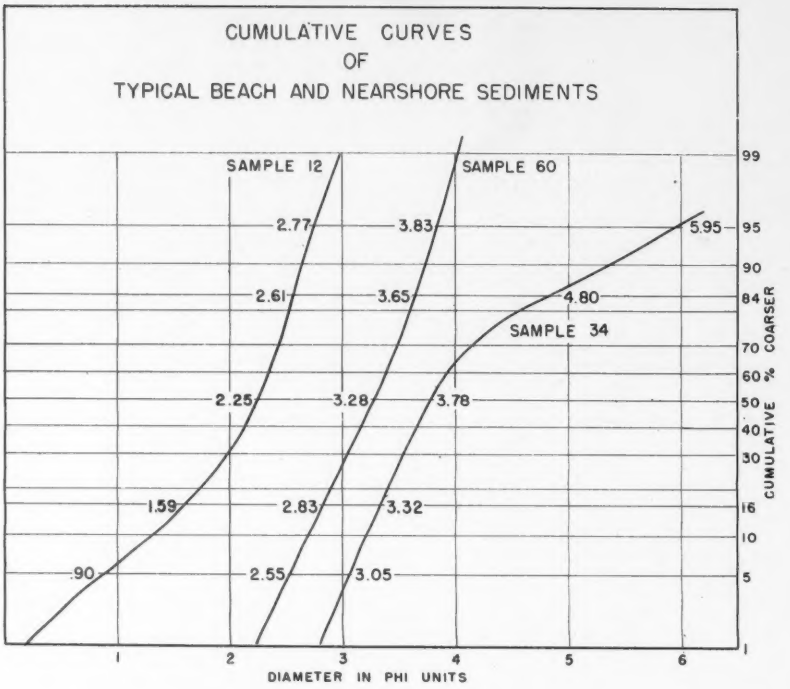


FIG. 5.

median of the total sample is not necessarily equal to the average of the medians of the laminae.

The measure of the mean recommended here is the average of the 16th and 84th percentile diameters and is essentially the same measure suggested by Otto (1939). This definition was selected because it is a good approximation to the mean obtained by moment measures for a large variety of distributions (compare the phi mean diameters of table 3a with the means obtained by moment measures given in table 5).

The mean and the median are equal in symmetrical distributions, but differ from each other in asymmetrical distributions. Geometrically, the median is the diameter value of the ordinate that divides the frequency distribution curve into two equal areas, while the arithmetic mean is the diameter value of the center of gravity of the frequency distribution (see figure 6). In this sense, the phi mean recommended here, M_ϕ, is arithmetic in that the independent variable of the frequency distribution curve is plotted in the arithmetic phi scale. With reference to the millimeter scale from which the phi units are derived ($\phi = -\log_2$ of diameter in millimeters), M_ϕ is a logarithmic mean. This follows, because if the phi scale of the independent variable were replaced by its equivalent in millimeters, the scale of the independent variable would become logarithmic. On the other hand, when converted to its diameter equivalent in millimeters, the

TABLE 4.—*Computation of the first four data moments of sample 12*[1]

(1) Class Limits, ϕ units	(2) Class Mark x_i	(3) f	(4) u	(5) uf	(6) u^2	(7) u^2f	(8) u^3	(9) u^3f	(10) u^4	(11) u^4f
<-1		.05	−6	− .30	36	1.80	−216	− 10.80	1296	64.80
−1 to −½	−0.75	.06	−5	− .30	25	1.50	−125	− 7.50	625	37.50
−½ to 0	−0.25	.49	−4	− 1.96	16	7.84	− 64	− 31.36	256	125.44
0 to ½	+0.25	1.70	−3	− 5.10	9	15.30	− 27	− 45.90	81	137.70
½ to 1	0.75	3.70	−2	− 7.40	4	14.80	− 8	− 29.60	16	59.20
1 to 1½	1.25	7.00	−1	− 7.00	1	7.00	− 1	− 7.00	1	7.00
1½ to 2	$x_0=1.75$	18.00	0							
2 to 2½	2.25	45.00	1	45.00	1	45.00	1	45.00	1	45.00
2½ to 3	2.75	23.10	2	46.20	4	92.40	8	184.80	16	369.60
>3		.90	3	2.70	9	8.10	27	24.30	81	72.90
Totals		100.00		+71.84		+193.74		+121.94		+919.14
Moments about x_0			$v_1=+0.178$		$v_2=+1.937$		$v_3=+1.219$		$v_4=+9.191$	
Mean			$M=n_1=cv_1+x_0=2.11$ phi							
Moments about M			$m_2=c^2(v_2-v_1^2)=0.354$ $m_3=c^3(v_3-3v_1v_2+2v_1^3)=-0.277$ $m_4=c^4(v_4-4v_1v_3+6v_1^2v_2-3v_1^4)=0.827$							
Standard deviation			$\sigma=\sqrt{m_2}=0.59$ phi							
Skewness			$\alpha_3=m_3/\sigma_3=-1.35$							
Kurtosis			$\beta_2=m_4/\sigma_4=6.60$							

[1] The cumulative frequency curve for this sample is shown in figure 5 and the frequency distribution curve in figure 6.

TABLE 5.—*Descriptive parameters of sediments computed from moment measures, using phi notation and class intervals of ½φ*[1]

Parameter	Sample Number			
	3	12	34	60
Phi mean diameter, M	0.26	2.11	4.03	3.25
Standard deviation, $\sigma=\sqrt{m_2}$	0.51	0.59	0.88	0.41
Skewness, $\alpha_3=m_3/\sigma_3$	1.70	−1.35	2.08	−0.38
Kurtosis, $\beta_2=m_4/\sigma_4$	3.10	6.60	4.90	2.70

[1] In order to compute the moments for these open ended distributions it was necessary to assume a finite distribution. This accounts for some of the discrepancies between these parameters and their graphic equivalents listed in table 3a. In comparing these parameters with the graphic measures it should be noted that α_3 equals approximately $6\alpha_\phi$, and that when $\beta_2=3$, $\beta_\phi\doteq 2/3$ (see figure 9).

phi arithmetic mean becomes the geometric mean of the size distribution in millimeters.[8]

Measure of Dispersion (*Sorting*)—In the phi notation the standard deviation of a frequency distribution can be approximated graphically for many distributions by obtaining one-half the distance between the 16th and 84th percentile diameters on a cumulative frequency curve. The relation recommended

$$\sigma_\phi=\tfrac{1}{2}(\phi_{84}-\phi_{16})$$

was suggested for sediment studies by Krumbein (1938) and Otto (1939), and is referred to here as the phi deviation measure.

[8] This becomes more apparent if the antilog of the mean, $M_\phi=\frac{1}{2}(\phi_{16}+\phi_{84})$ is taken. The antilog of M_ϕ is $\sqrt{(P_{16})(P_{84})}$, where $P_{16}+P_{84}$ are the 16th and 84th percentile diameters in millimeters. This latter expression is obviously geometric. For further reference see Krumbein and Pettijohn, 1938, pp. 240–245.

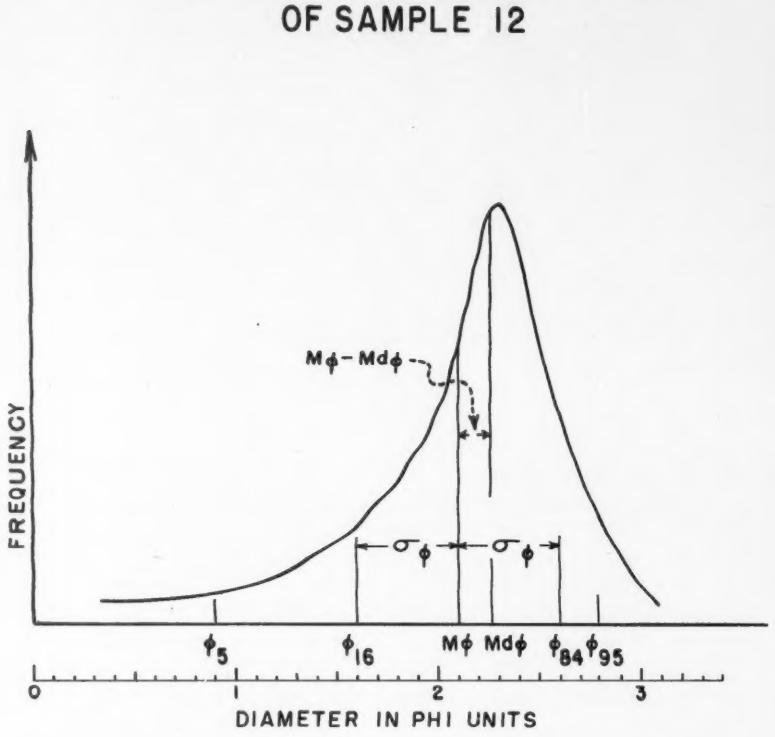


FIG. 6.

The geometric significance of σ_ϕ is shown in figures 4 and 6. It will be observed, that the phi deviation measure gives the standard deviation of the curve in terms of Wentworth units, since one phi unit is equivalent to one Wentworth division. For example, samples 3 and 12 (table 3) have σ_ϕ values of approximately 0.5 phi, and hence the spreads of their distribution curves between the phi mean and the 16th or 84th percentile diameters are one-half of a Wentworth unit. Sample 34 has a σ_ϕ of 0.74, and thus its spread is approximately 1.5 times greater than that of samples 3 and 12.

In general the value of σ_ϕ deviates

from the moment standard deviation as the distribution becomes more skew. The deviations from the moment standard deviation are discussed in the appendix (also see figure 8).

Measures of Skewness—In a symmetrical distibution the mean and the median coincide, but if the distribution is skewed the mean departs from the median, and the extent of this departure may be used as a measure of skewness. However, the skewness determined in this manner is not independent of the spread or deviation of the distribution. In order to secure an index that is independent of the spread of the curve, and thus may be compared with similar measures derived from other distributions, it is necessary to divide the departure of the mean from the median by the standard deviation of the distribution. The measure recommended is the phi skewness measure and is defined as follows:

$$\alpha_\phi = \frac{\frac{1}{2}(\phi_{16}+\phi_{84}) - Md_\phi}{\sigma_\phi} = \frac{M_\phi - Md_\phi}{\sigma_\phi}.$$

This measure of skewness is related to the moment skewness, α_3, of statistics by the approximate relationship,[9] $\alpha_3 = 6\alpha_\phi$. The limitations to the phi skewness are discussed in the appendix.

The phi skewness measure is zero for a symmetrical size distribution. If the distribution is skewed towards smaller phi values (coarser diameters), the phi mean is numerically less than the median and the skewness is negative, (see figure 6). Conversely, α_ϕ is positive for distributions skewed towards higher phi values.

The sign of the skewness can be ascertained by inspection of the cumulative curve of the distribution. The mean of the distribution is given by the intersection of a straight line drawn between ϕ_{16} and ϕ_{84} with the 50 per cent line (see figure 4). If this point is greater than the median, the curve has a positive skewness. It should be noted that this straight line, drawn between the 16th and 84th percentiles on probability paper, represents a normal distribution having the same mean and standard deviation as the distribution under consideration, and that the value of the phi skewness measure gives, to the first approximation, the amount of the departure of the distribution from the normal.

The use of a secondary measure of skewness, called the second phi skewness measure, based on the 5th and 95th percentile diameters is also recommended. This measure has the same form as the primary skewness discussed above, and is defined as:

$$\alpha_{2\phi} = \frac{\frac{1}{2}(\phi_5+\phi_{95}) - Md_\phi}{\sigma_\phi}.$$

The significance of this measure can be illustrated graphically by constructing a straight line between ϕ_5 and ϕ_{95} (see figure 4). In this case the straight line represents a normal distribution, having the same spread between the 5th and 95th percentile diameters as the curve under consideration. Thus $\alpha_{2\phi}$ is another measure of the departure of the curve from a normal distribution.

While the primary skewness measure α_ϕ is sensitive to skew properties occurring in the bulk of the grain-size distribution, the secondary skewness $\alpha_{2\phi}$ is most sensitive to the distribution within the tails of the sediment. Also, $\alpha_{2\phi}$ serves as a check on the continuity of the skew properties of a distribution, since it is numerically larger than α_ϕ for most simple distributions. In this connection, a skewness ratio, $R_\phi = \alpha_{2\phi}/\alpha_\phi$, is useful. A value of R_ϕ of approximately 2.7 is common, over a fairly wide range of skewness, if the curve can be approximated by either a Pearson Type III distribution or two terms of a Gram-Charlier series (see appendix). The use of R_ϕ in determining the type of distribution and the limitations to this system of graphic approximation to moment measures is discussed

[9] Statistics texts (for example, Walker, 1947, p. 158; Mills, 1938, p. 158, and Yule & Kendall, 1948, p. 162) give an approximate formula for skewness,

$$\alpha_3 = \frac{6(\text{Mean} - \text{Median})}{\text{Standard Deviation}}.$$

in the appendix and illustrated in figure 9.

The inclusion of the second skewness, together with the other measures, allows five significant points (ϕ_5, ϕ_{16}, ϕ_{50}, ϕ_{84} and ϕ_{95}) of the cumulative curve of a sediment distribution to be obtained from the listed data without resort to the original mechanical analysis of the distribution. Thus, if the five parameters are listed for a grain-size distribution, five significant points on the cumulative curve of the distribution may easily be computed (see table 1). This would increase the value of the data listed for a sediment in a report, and in many cases would eliminate the necessity of including the complete mechanical analysis of the sediment.

Measure of Kurtosis—Kurtosis is a measure of peakedness, and statistically is related to the fourth moment about the mean. There appears to be no simple graphic analogy for this moment. However, a measure sensitive to the peakedness of a distribution, the phi kurtosis measure, is defined as follows:

$$\beta_\phi = \frac{\frac{1}{2}(\phi_{16}-\phi_5)+\frac{1}{2}(\phi_{95}-\phi_{84})}{\sigma_\phi} = \frac{\frac{1}{2}(\phi_{95}-\phi_5)-\sigma_\phi}{\sigma_\phi}.$$

The phi kurtosis measure is a dimensionless measure of the average spread between the percentile diameters ϕ_5, ϕ_{16} and ϕ_{84}, ϕ_{95}, and is shown graphically in figure 4 as the quantity $\frac{1}{2}(a_1+a_5)$ divided by the standard deviation. This measure may be thought of as the ratio of the average spread in the tails of a distribution to the standard deviation of the distribution and thus is a measure of the degree of peakedness. For a normal distribution β_ϕ has a value of 0.65. If the distribution is less peaked than the normal, the tails have a greater spread as represented by the average distance between ϕ_5, ϕ_{16} and ϕ_{84}, ϕ_{95} and β_ϕ is greater than 0.65. Conversely, values of β_ϕ less than 0.65 indicate that the distribution is more peaked than normal.

Three of the sediment samples used for illustration in this paper are less peaked than normal, while the fourth, no. 60, has a β_ϕ value of 0.57, and is therefore more peaked than normal. The phi kurtosis measures for these samples are listed in table 3a, and the corresponding moment kurtosis β_2 are listed in table 5.

APPENDIX

The following discussion of moment measures and theoretical frequency distributions is given as an aid in understanding the relationship and limitations of the graphic parameters suggested in this paper to the analogous measures commonly used in statistics. The discussion of statistics is necessarily brief and limited in scope, and only those phases essential to the present study are considered. More detailed information regarding this subject may be obtained from textbooks on statistics (also see Krumbein & Pettijohn, 1938, Chapters 8 & 9).

Moment Measures—The term "moment" has its origin in mechanics, where the "moment of a force" is used to denote the product of a force and a distance from some origin, usually referred to as the fulcrum point. In statistics the frequency of the distribution replaces the "force" of mechanics, and the term statistical moment implies moment per unit frequency.

In mathematical statistics it is common practice to describe a frequency distribution in terms of moment measures. In general the first four moments provide an adequate description of a distribution, which when converted to the proper form are referred to as the mean, standard deviation, skewness, and kurtosis. In calculus notation, the "theoretical moment" of a distribution about the origin is defined as:

$$(1) \qquad n_k = \frac{1}{N}\int_{-\infty}^{+\infty} x^k f(x)\,dx$$

where N is the total frequency, and $f(x)$ is the frequency function. The desired moment is obtained by setting k equal to 1, 2, 3, or 4. In practice, the equation for the frequency distribution $f(x)$ is

usually not known. In this case it is customary to classify the data by dividing the distribution into equal class intervals in a manner similar to that used in constructing a histogram. The moment measures are then obtained by summing the individual moments for each class interval. A measure obtained in this manner will be referred to as the "data moment" about the origin, and is defined as:

$$(2) \qquad n_k=\frac{1}{N}\sum_{i=1}^{h} x_i^k f_i$$

where x_i is the class mark (value of the mid-point of the class interval) of the ith class, f_i is the class frequency, and h is the number of classes.

Certain assumptions are made in the computation of data moments which in general make them less exact than theoretical moments. For example, it is assumed that the frequencies, f_i, can be considered as centered at the class marks, x_i. Thus if the data moments are to approach the value of the corresponding theoretical moments, it is necessary that the number of classes, h, be relatively numerous. Corrections for data moments are considered in most statistics texts, and will not be described here.

The first moment about the origin of the distribution, n_1, is the arithmetic mean and will be designated as M. It is customary to compute the remaining three moments about the mean of the distribution rather than the origin. Data moments about the mean are defined as:

$$(3) \qquad m_k=\frac{1}{N}\sum_{i=1}^{h} (x_i-M)^k f_i.$$

Because the computation of data moments from their definitions (equations 2 & 3) is very tedious, it is convenient to use a short method based on a new variable, u, which takes on only small integral values. This variable is defined as $u=(x_i-x_0)/c$, where x_0 is a class mark chosen near the mean of the distribution, and c is the class interval. The class mark x_0, where u equals zero, becomes the origin when computing moments by the short mehod, and the various moments as defined by equation 2 then become moments about x_0 and will be denoted by v_k. These measures are converted to the appropriate moments about the origin and mean of the distribution by the following equations:

$$(4) \qquad n_1=M=cv_1+x_0$$

$$(5) \qquad m_2=c^2(v_2-v_1^2)$$

$$(6) \qquad m_3=c^3(v_3-3v_1v_2+2v_1^3)$$

$$(7) \qquad m_4=c^4(v_4-4v_1v_3+6v_1^2v_2-3v_1^4)$$

The computations of the first four moments of sample 12 are shown in table 4. The class interval, c, used in this computation is ½ phi, and the total number of classes, h, is 10. The first column gives the class limits in phi units, the second column lists the midpoint or class mark, x_i, for each class, and the frequency for each class, f, in per cent is listed in column 3. The variable u is shown in column 4, with the zero value chosen in the class range 1.5 to 2 phi. Thus, the arbitrary origin, x_0, for the short computation is the midpoint of this class, and is equal to 1.75 phi.

The product of columns 3 and 4 gives the first moment for each class. The algebraic sum of these products (column 5), divided by the total percentage (100) gives, v_1, the first moment about x_0 as origin. The arithmetic mean, M, which is the first moment about the phi origin is obtained from equation 4. This equation gives a value of 2.11 phi units for M.

The second, third, and fourth moments about x_0 are given at the ends of columns 7, 9, and 11 respectively. Conversion of these measures to moments about the mean by equations 5, 6 and 7 give the following values:

$$m_2=+0.354$$
$$m_3=-0.277$$
$$m_4=+0.827.$$

The standard deviation is defined as $\sigma=\sqrt{m_2}$ and is 0.59 phi unit for this distribution. The skewness measure α_3

is defined as m_3/σ^3 and is equal to -1.35. For a symmetrical distribution the skewness is zero; the negative sign of the skewness of sample 12 indicates that the median is greater (in phi units) than the mean diameter.

The moment measure of kurtosis is defined as $\beta_2 = m_4/\sigma^4$. For a normal distribution β_2 equals 3; if the distribution is more peaked than the normal β_2 is less than 3 and if the distribution is less peaked β_2 is greater than 3. The computations shown in table 4 give a value of 6.6 for β_2, indicating that the distribution is less peaked than a normal distribution.

The data moment measures for sample 12 were also computed using a class interval of $\frac{1}{4}$ phi, and 22 classes. The values of M, σ, α_3, and β_2 by this computation (not shown) were 2.11, 0.58, -1.46, and 5.8 respectively. These values are probably more nearly equal to the theoretical moment measures because the class interval is smaller and the number of classes are greater. The data moment measures, using a class interval of $\frac{1}{2}$ phi, for the four samples illustrated in this paper are listed in table 5.

Theoretical Distributions—Because data moments of distributions are more variable than theoretical measures, it is advisable to compare the approximate graphic measures recommended in this paper with theoretical moment measures of known distributions. Four common distributions which frequently apply to sediments are used for purposes of comparison; two of these, the Gram-Charlier series and the Pearson Type III are described below. The former is particularly useful for comparison because it is basically a normal distribution with skewness and kurtosis terms which are additive. Under certain conditions (Smith and Duncan, 1945, p. 84) the frequency distribution function for a Gram-Charlier series may be written:

$$f(x) = \frac{100}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}t^2}\left[1 - \frac{\alpha_3}{2}(t - \tfrac{1}{3}t^3) + \frac{\beta_2 - 3}{8}(1 - 2t^2 + \tfrac{1}{3}t^4)\right] \tag{8}$$

where $t = (x - M)/\sigma$ is a variable called a standard unit, e is the base of natural logarithms, and M, σ, α_3, and β_2 are respectively the theoretical mean, standard deviation, skewness, and kurtosis which were defined previously.

The cumulative frequency $F(x)$ between M and x, or between $t = 0$ and $t = (x - M)/\sigma$, is obtained by integrating $f(x)dx$, and may be written:[10]

$$F(x) = \frac{100}{\sqrt{2\pi}} \int_0^t e^{-\frac{1}{2}t^2} dt - \frac{50\alpha_3}{3\sqrt{2\pi}}\left[1 - e^{-\frac{1}{2}t^2}(1 - t^2)\right] + \frac{25}{6\sqrt{2\pi}}(\beta_2 - 3)\left[e^{-\frac{1}{2}t^2}(3t - t^3)\right] \tag{9}$$

where $dx = \sigma dt$. The first term is the integral of the normal distribution, while the second and third terms, which are additive, express the skewness and kurtosis of the distribution. In a normal distribution $\alpha_3 = 0$, $\beta_2 = 3$, and the second and third terms vanish. The value of each of these terms for any value of t may be obtained from standard tables of the normal curve and its derivatives.

The Pearson Type III distribution, sometimes referred to as the incomplete Gamma function, is described in detail by Pearson (1922, p. v–xxxi) in the introduction to the tables of this function. The frequency distribution function may be written as:

$$f(x) = Ae^{-w}w^p \tag{10}$$

and the cumulative per cent function as:

$$F(x) = A\int_0^w e^{-w}w^p dw \tag{11}$$

where A is a constant chosen so that $F(x)$ equals 100 per cent when w approaches infinity, $w = px/a$, and a and p are constants related to the moment measures as follows:

$$M = \frac{p+1}{p}a \tag{12a}$$

$$\sigma = \frac{\sqrt{p+1}}{p}a = 1 \tag{12b}$$

[10] The first two terms of equation (9) are developed in Otto, 1939, page 74.

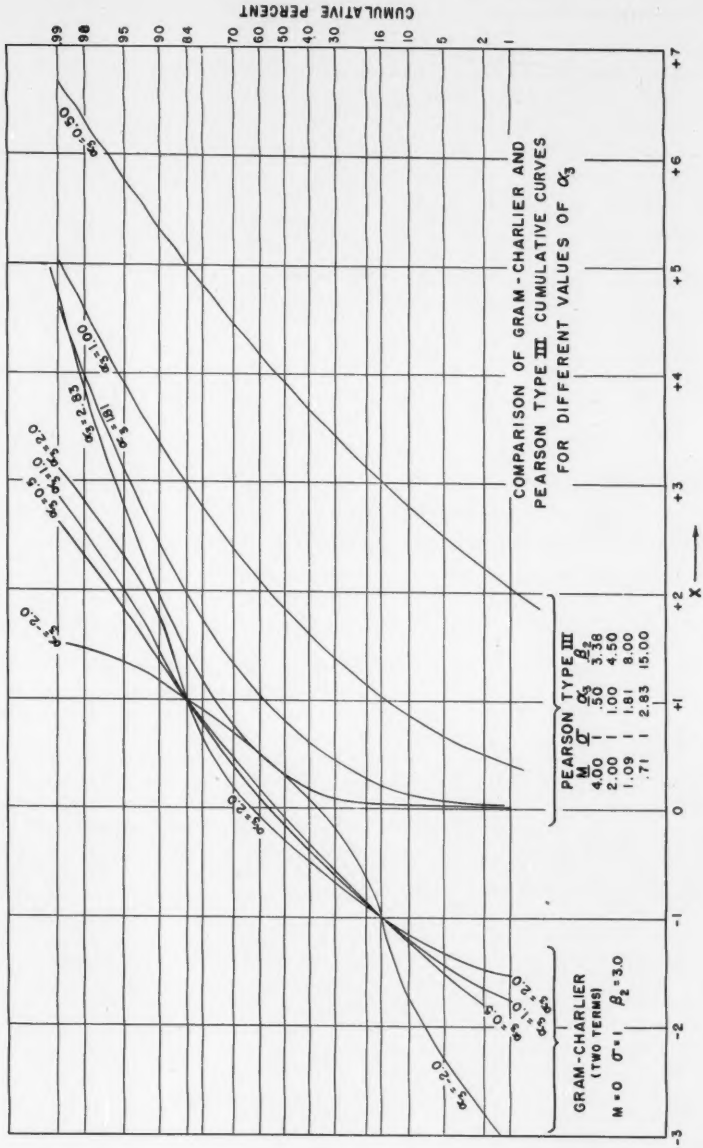
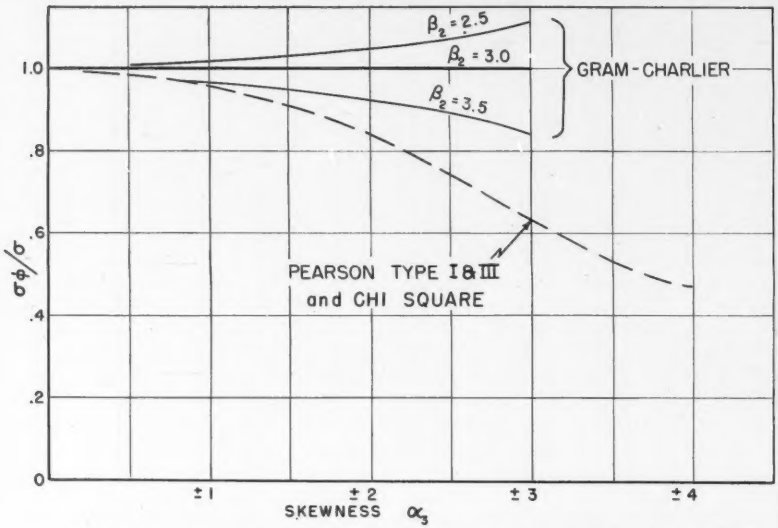

CUMULATIVE PERCENT
99
98
95
90
84
70
60
50
40
30
16
10
5
2
1
-3
-2
-1
0
+1
+2
+3
+4
+5
+6
+7
X
COMPARISON OF GRAM-CHARLIER AND
PEARSON TYPE III CUMULATIVE CURVES
FOR DIFFERENT VALUES OF α_3
PEARSON TYPE III
M σ α_3 β_2
4.00 1 .50 3.38
2.00 1 1.00 4.50
1.09 1 1.81 8.00
.71 1 2.83 15.00
GRAM-CHARLIER
(TWO TERMS)
M = 0 σ = 1 β_2 = 3.0
α_3=-2.0
α_3=-1.0
α_3=-.5
α_3=0
α_3=.5
α_3=1.0
α_3=2.0
α_3=-.50
α_3=-1.00
α_3=-2.83
α_3=-4.81
α_3=-.5
α_3=-1.0
α_3=-2.0
α_3=2.0

FIG. 7.



RELATION BETWEEN DEVIATION MEASURE AND THEORETICAL SKEWNESS

FIG. 8.—Ratio of the phi deviation measure, σ_ϕ, to the theoretical standard deviation, σ, as a function of the theoretical skewness, α_3.

$$\alpha_3 = \frac{2}{\sqrt{p+1}} \tag{12c}$$

$$\beta_2 = 3 + \frac{6}{p+1}. \tag{12d}$$

For a distribution to be of the Pearson Type III it is necessary and sufficient that

$$2\beta_2 - 3\alpha_3^2 - 6 = 0.$$

This type distribution is skewed, and its frequency distribution curve as described by equation 10 has one finite end at $x=0$, while the other tail approaches zero as a limit as x becomes infinite. In the Pearson notation above, the x origin is at the finite end of the curve and the distribution has a standard deviation of one x unit. This notation may be used with some other variable, y, by the following transformation,

$$x = \frac{y - M_y}{\sigma_y} + \sqrt{p+1} \tag{13}$$

where M_y and σ_y are the mean and standard deviation in the units of the y variable, and p is determined from α_3 in equation 12c.

Examples of Gram-Charlier and Pearson Type III cumulative frequency curves are shown in figure 7. Numerous cumulative curves representing both of these types were drawn by entering selected values of the theoretical moment measures in equations 9 and 11. In addition to the Pearson Type III and the Gram-Charlier distributions described above, numerous curves representing Pearson Type I[11] and Chi square[12] distributions were also drawn. The graphic measures M_ϕ, σ_ϕ, α_ϕ, $\alpha_{2\phi}$ and β_ϕ were computed for each curve, and compared

[11] The Pearson Type I distribution is sometimes referred to as the incomplete Beta-function (Pearson, 1934).

[12] See Fisher & Yates, 1948, and Kenney & Keeping, 1951, p. 98.

with the corresponding theoretical measure M, σ, α_3 and β_2. The results of these comparisons are given in figures 8 and 9.

Figure 8 shows the relation of σ_ϕ to the theoretical standard deviation, σ, for Gram-Charlier, Pearson Type I and III and Chi square distributions as a function of the theoretical skewness α_3. For skewness values near zero, σ_ϕ serves as a good approximation to the theoretical standard deviation. For higher degrees of skewness, σ_ϕ deviates appreciably from σ for the Pearson and Chi square type distributions, but serves as a fair approximation to the theoretical standard deviation for Gram-Charlier distributions if β_2 falls between 2.5 and 3.5.

Figure 9 shows the relation of the theoretical skewness α_3 to the phi skewness measure α_ϕ, the phi kurtosis measure β_ϕ, and the ratio of the two phi skewness measures, R_ϕ. The shaded areas in this figure represent confidence limits, such that a distribution whose β_ϕ and R_ϕ fall within their respective shaded areas, will have a theoretical skewness α_3 within the range of the shaded area opposite the phi skewness measure α_ϕ. This figure indicates that a good approximation to the theoretical skewness can be obtained for values of α_ϕ between -0.2 and $+0.2$.

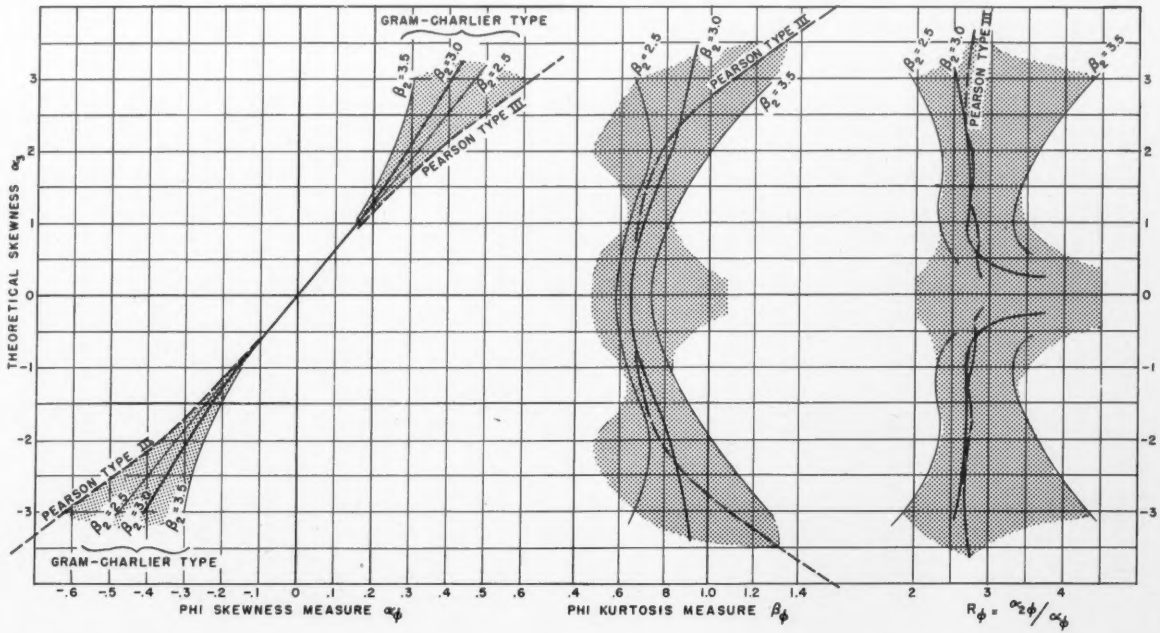
The approximation of the graphic measures to the corresponding theoretical moment measures decreases as the skewness of the distribution increases. Samples 3, 12 and 34 were chosen for illustration because they represent distributions with relatively high degrees of skewness for which it is difficult to deduce the theoretical measures from the graphic measures. For example consider samples 3 and 12. The phi graphic measures listed in table 3a suggest that, with the exception of the sign of the skewness, the distributions are quite similar. Plotting the phi skewness measure values of $+0.28$ and -0.29 in figure 9 together with the respective values of β_ϕ and R_ϕ shows that the distributions agree quite well with either the Pearson, the Chi square, or the Gram-Charlier type with $\beta_2 = 3.0$. This indicates that the theoretical skewness for either sample could fall between values of 1.6 and 2.0. If it is assumed that the distributions are either of the Pearson Type III, or Gram-Charlier ($\beta_2 = 3.0$), and that their α_3 values are between 1.6 and 2.0, then from figure 8 it can be shown that the ratio of σ_ϕ/σ must fall between 0.84 and 1.00. Since the samples have σ_ϕ values of approximately 0.5 phi, their theoretical standard deviations will fall between 0.5 and 0.6 phi.

Curve fitting techniques (described in most statistics texts) aided by the data moment measures for the samples shows that the distribution of sample 3 can best be described by a Gram-Charlier series with $\sigma = 0.50$ phi, $\alpha_3 = +2.0$, and $\beta_2 = 3.0$, while sample 12 is best described by a Pearson Type III distribution with $\sigma = 0.56$ phi, $\alpha_3 = 1.60$ and $\beta_2 = 6.6$. The general form of the theoretical distributions for these two curves are given approximately in figure 7, by the Gram-Charlier curve having $\alpha_3 = 2.0$ and the Pearson Type III with $\alpha_3 = 1.81$.

The above analysis indicates that for distributions similar to 3 and 12, the theoretical mean, standard deviation, and skewness can be ascertained from the graphic phi measures, with about the same accuracy as is obtained from rough data moments. However, the phi kurtosis measure of distributions with this high degree of skewness cannot be used as an index of theoretical moment kurtosis. The phi kurtosis measure is only satisfactory in this regard for lower skewness values, altho it is a useful measure of the average spread in the tails of a distribution for all degrees of skewness.

CONCLUSIONS

Adoption of the graphic measures listed in table 1 would lead to a standardization of the descriptive measures for the grain-size distribution of sediments that is based on more rigorous statistical concepts than are most measures now in use. These measures have the advantage of being approximate graphic equivalents to the moment measures commonly em-



RELATION BETWEEN THEORETICAL SKEWNESS AND GRAPHIC PHI MEASURES

FIG. 9.—Relation between the theoretical skewness, α_3, and the graphic phi measures. Shaded areas represent confidence limits, such that a distribution whose R_ϕ and β_ϕ fall within their respective shaded areas will have a theoretical skewness value within the range of the shaded area opposite the phi skewness measure. The relation between theoretical skewness and α_ϕ, β_ϕ and R_ϕ for the Pearson Type III also applies approximately for Pearson Type I and Chi-square distributions.

ployed in mathematical statistics, but are quickly and easily computed from five percentile diameters obtained from the cumulative frequency curve of the sediment.

The analogy between these measures and the moment measures of statistics should prove to be useful in many types of sediment studies. For example, it seems more meaningful to use measures of this type when investigating the relation between the grain-size distribution of transported material and the statistical distributions of properties in the transporting media.

REFERENCES

BAKER, H. A. (1920) On the investigation of the mechanical constitution of loose arenaceous sediments by the method of elutriation, etc.: Geol. Magazine, vol. 57, pp. 366–370.

DOEGLAS, D. J. (1946) Interpretation of the results of mechanical analyses: Jour. Sedimentary Petrology, vol. 16, pp. 19–40.

FISHER, R. A. and YATES, FRANK (1948) Statistical tables for biological, agricultural and medical research. London, Oliver and Boyd. 112 pp.

GADDUM, J. H. (1945) Lognormal distributions: Nature, vol. 156, pp. 463–466.

HAZEN, ALLEN (1914) Storage to be provided in impounding reservoirs for municipal water supply: Trans. Am. Soc. Civil Eng., vol. 77, pp. 1539–1669.

KENNEY, J. F. and KEEPING, E. S. (1951) Mathematics of statistics (part II), D. Van Nostrand Co., Inc., 429 pp.

KRUMBEIN, W. C. (1934) The probable error of sampling sediments for mechanical analysis: Amer. Jour. Sci., vol. 27, No. 159, pp. 204–214.

KRUMBEIN, W. C. (1936a) Application of logarithmic moments to size frequency distribution of sediments: Jour. Sedimentary Petrology, vol. 6, pp. 35–47.

KRUMBEIN, W. C. (1936b) The use of quartile measures in describing and comparing sediments: Amer. Jour. of Sci., vol. 32, No. 188, pp. 98–111.

KRUMBEIN, W. C. (1938) Size frequency distributions of sediments and the normal phi curve: Jour. Sedimentary Petrology, vol. 8, pp. 84–90.

KRUMBEIN, W. C. and PETTIJOHN, F. J. (1938) Manual of sedimentary petrography, D. Appleton-Century Co., Inc., 549 pp.

MILLS, F. C. (1938) Statistical methods applied to economics and business, Henry Holt & Co., 746 pp.

OTTO, G. H. (1939) A modified logarithmic probability graph for the interpretation of mechanical analyses of sediments: Jour. Sedimentary Petrology, vol. 9, pp. 62–76.

PEARSON, KARL (ed.) (1922) Tables of the incomplete Gamma-function etc., London, Dept. of Scientific and Industrial Research, 164 pp.

PEARSON, Karl (ed.) (1934) Tables of the incomplete Beta-function, Cambridge, University Press, 494 pp.

POOLE, D. M., BUTCHER, W. S., and FISHER, R. L. (1951) The use and accuracy of the Emery settling tube for sand analysis: Beach Erosion Board Tech. Mem., No. 23.

SMITH, J. G. and DUNCAN, A. J. (1945) Sampling statistics and applications, fundamentals of the theory of statistics, McGraw-Hill Co., 498 pp.

TRASK, P. D. (1932) Origin and environment of source sediments of petroleum, Houston, Gulf Pub. Co., 323 pp.

Walker, H. M. (1947) Elementary statistical methods, Henry Holt & Co., 368 pp.

YULE, G. U., and KENDALL, M. G. (1948) An introduction to the theory of statistics, Charles Griffin & Co., 570 pp.

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FIGS. 1–2, SEPTEMBER, 1952

CLAY AND OTHER NON-CARBONATE MINERALS IN SOME LIMESTONES

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ABSTRACT

The minerals in acid-insoluble residues, 2 microns and less in diameter, from 27 limestones and dolomites, ranging in age from Cambrian to Recent, both marine and non-marine in origin were determined qualitatively. Quartz is widespread and abundant. Illite is the dominant clay mineral in both marine and non-marine carbonate rocks. Kaolinite is most likely to occur in Mississippian and Pennsylvanian limestones, and may be more common in non-marine than in marine rocks. Montmorillonite was found to be the prominent clay mineral in the Bethany Falls (Pennsylvanian) and in one bed of the Morrison limestones.

INTRODUCTION

The relatively coarse-grained fractions of acid insoluble residues from limestones and dolomites are examined from many thousands of samples each year, but relatively few mineral analyses have been published on the fine, clay-sized insoluble residues. Grim, Lamar, and Bradley (1937) reported on the clay minerals in the fine fraction of the insoluble residues from thirty-five Illinois limestone and dolomite samples, in what was probably the first paper on this subject. This paper will report on the minerals present in the size fraction less than 2 microns in effective settling diameter of the HCl acid-insoluble residues from 27 limestone and dolomite samples of marine and fresh water origin ranging in age from early Paleozoic to Recent.

LABORATORY PROCEDURE

Approximately 100 to 200 grams of each limestone sample were dissolved in 6 N HCl after which the insoluble residue was washed with distilled water until free from chloride ions. The washed residue was then size-fractionated in distilled water, or occasionally in a .01N sodium oxalate solution, to recover the portion less than 2 microns in effective settling diameter. This clay-size fraction was dried at 65°C. and gently reground to pass a 100-mesh sieve.

Treatment of dolomites in acid strong enough to dissolve the dolomite mineral does not affect kaolinite or illite significantly, but may attack montmorillonite, as was observed by Nutting (1941). To obtain more quantitative data on the amount of solution, the writers treated a weighed quantity of Wyoming montmorillonite, which had been mixed with an excess of calcite (to simulate a natural clay in limestone), with 6 N HCl and allowed it to stand for 96 hours, the maximum time taken to dissolve some dolomites in cold dilute HCl. The undissolved clay remaining was washed free from chloride ions, centrifuged, and dried. Over 50 per cent (57.1%) of the original montmorillonite sample had been dissolved. Hence, the action of HCl on montmorillonite may be more severe than reported by Brindley (1951, p. 24), "Thus dilute HCl will remove carbonates, and, if warm, may remove chlorites and also some forms of mica and montmorillonite, though most forms of the two latter minerals are generally resistant to the treatment." The wash water from the undissolved montmorillonite clay residue and the original acid solution were combined and evaporated to dryness. An X-ray diffraction pattern of the dried residue shows prominent quartz

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lines, the possible presence of aluminum oxide trihydrate (?), and other unidentified lines. The quartz present negates Nutting's conclusion (1941, p. 233) that "at acid concentrations 20% or over, bases but no silica go into solution, and no hydrosols are formed."

Because of the solution of montmorillonite by HCl some montmorillonite may not have been found and reported in the residue of the limestones although present in the original rock, and also the quantity of montmorillonite observed and reported can be expected to be less than originally and actually present. Weaker acids than HCl may be used to dissolve calcite limestone, but dolomites require more drastic solvents. It was decided in this investigation to standardize on 6N HCl for all rocks.

The dried, and insoluble fractions less than 2 microns in diameter from the limestone were then analyzed by the conventional techniques for determining clay minerals. These included X-ray diffraction on film (a few with spectrometer) using Ni-filtered, CuKα radiation, differential thermal analysis (Berkelhammer, 1945) apparatus, petrographic and index oil immersion methods, and staining techniques (Faust, 1940; Mielenz, Ring, and Schultz, 1950) although the unreliability of the latter (Page, 1941) is recognized. With some of the clay fractions a single technique was diagnostic of qualitative mineral determination, but with others several methods were necessary (further details in Robbins, unpublished Master's thesis, 1952).

Although quantitative clay mineral analysis is highly desirable, it is not believed possible to express with confidence the quantities of minerals found in the residues described in this report any more precisely than by terms such as abundant, scanty, or about equal in quantity. It is doubtful, in general, if current analytical methods permit precise quantitative mineral analyses of *natural* mixtures of clay minerals where the samples come from radically different sources as was the case in this project, although it is granted that *artificially* blended mixtures of relatively pure, well-developed end-member clay mineral components may be analyzed quantitatively and furnish excellent checks between "found" and "taken" quantities. Instrumental analytical records of clay mineral analyses may be clear-cut and sharply defined but natural mixtures of clays are subject to numerous variables which may modify the instrumental records more than do moderate differences in the quantities of clay minerals. Where clay rocks, *i.e.*, natural clay mineral mixtures, are taken from different geological locations, differences between the clays in crystal size, in perfection of crystallization, in isomorphous composition, in adsorbed impurities, in packing (natural particle density), etc., may make unreliable for precise quantitative purposes the comparison of their instrumental records. To ignore those variables may lead to a serious, false sense of precision about the data which themselves came from precise instruments. Until techniques for separating (purifying) clay mixtures into their components are improved, quantitative comparisons of random samples, such as were studied in this project, are subject to important possible error.

DEFINITION OF THE CLAY MINERALS

In this report, kaolinite refers to the clay minerals which show a 7A basal interplanar spacing, and which undergo strong endothermic and exothermic (DTA) reactions at about 600°C. and 980°C., respectively. Strict distinction is not made therefore between ideal kaolinite, and the "fire clay mineral" of Brindley, *et al.* and a probably similar kaolinite-like mineral described by Burst (1950), and halloysite ($2H_2O$). Some diffraction patterns show a wide band of diffuse darkening extending in both directions from the 7A position (fig. 1). Possibly this band indicates fine-grained, poorly crystallized, or degraded kaolinite, or is due to unknown conditions (not the sample holder). Independent

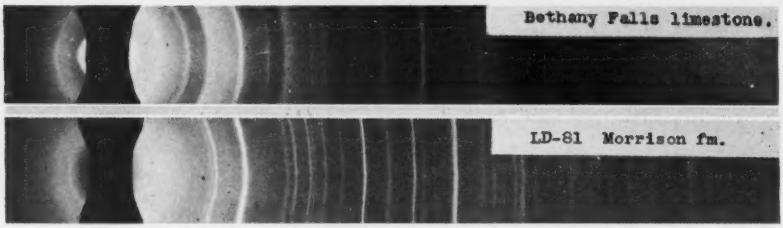

FIG. 1.—X-ray diffraction patterns of the clay-size minerals in the Bethany Falls and Morrison, LD-81, limestones. Quartz lines are present in both patterns. Montmorillonite predominates in the Bethany Falls as is shown by the strong line near the center of the pattern (17–18 A) and higher order basal spacing lines.

In LD-81, illite is indicated by the 10Å line, and a diffuse halo extends out to the 7A (kaolinite) position. The differential thermogram of LD-81 (fig. 2), indicates illite; the presence of kaolinite is doubtful.

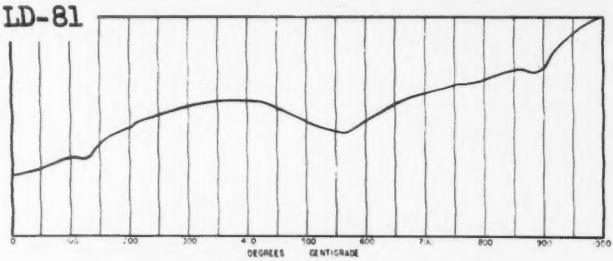

FIG. 2.—Differential thermogram of Morrison LD-81 limestone indicating illite; the presence of kaolinite is doubtful.

optical or DTA data are not always confirmatory, hence kaolinite is not reported without question unless the evidence is positive and clear cut.

Illite refers to the clay mineral with a 10A basal spacing which is not significantly expanded after solvating with ethylene glycol. It shows a characteristic endothermic peak (DTA) usually less than 625°C.

Montmorillonite refers to the clay group, the minerals of which expand readily to about 18A when solvated with ethylene glycol, and which show a characteristic endothermic peak (DTA) in the range of 650°–700°C.

That the above classification is vulnerable to serious criticism has been discussed by Weaver and Bates (1951) and Jackson, *et al.* (1952). However, lacking chemical analyses of the clays studied in this report, cations can not be assigned quantitatively to octahedral and tetrahedral positions, and the earlier, clay mineral classification is still used.

The occurrence of chlorite (sedimentary) has been suspected in several of the clays from the limestones but its diffraction lines are too weak and diffuse, if actually present, to make the determination of chlorite positive. The considerable amount of quartz, and in some cases organic matter, which make up a sizeable part of the clay-size residue lower the intensities of diagnostic instrumental measurements and presumably the threshold of clay mineral determination over what can be done with artificial systems.

It is not the purpose of these reserva-

tions to weaken confidence in the results of the mineral analyses, but rather it is intended to be realistic in order that one may know where to place strongest confidence. Students too frequently accept the precision and accuracy of printed analyses at their face value, for example to the second digit beyond the decimal point in ordinary chemical analyses of rocks whereas the first decimal digit or even the whole number may be in error. (See Fairbairn and others, 1950–51; Hillebrand, 1919.) Measured data should preferably be given with an appraisal of the likely error involved. With these preliminaries disposed of, the mineral residues may be considered.

LIMESTONES AND DOLOMITES, AND THEIR CLAY FRACTIONS

Bonneterre dolomite, marine, Cambrian, gray, fine to medium-grained. Locality, East Bonneterre, Mo. X-ray and DTA indicate that illite is the predominant clay mineral. A pronounced exothermic rise in the thermogram about 950°C., and a darkened diffuse band in the 7A region suggest the possible presence of a kaolin mineral. Quartz shows strongly in the X-ray pattern.

Derby-Doerun dolomite, Marine, Cambrian, gray to buff, fine-grained. Locality, one mile south of Elvins, Mo. Illite, quartz and organic matter are present.

Potosi dolomite, marine, Cambrian, light brown, medium to fine-grained. Locality, west edge of Potosi, Mo. Quartz lines are strong, but basal spacing of lines of illite and kaolinite are clearly distinguishable in the X-ray pattern.

Eminence dolomite, marine, Cambrian, light gray, medium-grained. Locality 3 miles southwest of Potosi, Mo., on Mo. State Highway No. 8. Quartz, illite and carbon constitute its clay-size components. A heavy but diffuse band is present in the kaolinite position.

Gasconade dolomite, marine, Ordovician, light gray, medium-grained. Locality, near the top of the Gasconade formation 5 miles southwest of Potosi, Mo., on Missouri State Highway No. 8. The clay-size residue was very scanty. Quartz lines are strong in the X-ray pattern, illite is clearly represented, and a weak diffuse kaolinite (?) band is shown.

Jefferson City dolomite, marine, Ordovician, light gray to tan, medium-grained. Locality, near the top of the formation in a road cut 4.1 miles west of Ashland, Mo., in the SE¼ sec. 12 T. 46 N., R. 13 W., Boone County. Quartz predominates in the X-ray pattern, but illite is represented, and a diffuse band is well developed where the kaolinite line would occur. The DTA is not clearly diagnostic but the presence of kaolinite is suggested.

Girardeau limestone, marine, Silurian, compact, fine-grained, bluish gray. Locality, 2 miles north of Cape Girardeau, Mo., on the Bend road. Quartz, illite, and considerable organic matter constitute the clay-sized fraction.

Ashland limestone, marine, Devonian, dark brownish-gray, coarsely crystalline. Locality, NE¼SW¼ sec. 12, T. 46 N., R. 12 W., 0.3 mi. north of Sycamore School, Boone County, Mo. Illite is clearly evident in the X-ray diffraction pattern, a diffuse kaolinite (?) band is present, and quartz is faintly shown.

Chouteau formation, marine, Mississippian Age. The Chouteau ranges from dolomite to calcite limestone. A gray, fine-grained limestone sample was collected from the Easley quarry, ¼ mile south of Easley, Mo., in southern Boone County. Well developed illite and quartz lines are present in the X-ray pattern. A strong exothermic band in the DTA is due to organic matter.

Burlington limestone, marine, Mississippian Age. A specimen from the Boone quarry, 0.3 miles south of Columbia, Boone County, Mo. is typically crinoidal, light gray, coarsely crystalline, and replete with crinoid stem plates. Montmorillonite, illite (?), and weak kaolinite and quartz lines are present in the X-ray diffraction pattern. The DTA accords with that determination.

Ste. Genevieve limestone, marine, Mississippian, dark gray, oolitic, and arenaceous. Locality, St. Genevieve, Mo.

Kaolinite is weakly shown in the X-ray pattern but can not be confirmed by the DTA which is non-diagnostic.

Bethany Falls limestone, marine, Pennsylvanian Age. The light-gray, thick, massive, escarpment-forming layer was sampled along U. S. highway 40 in eastern Jackson County, Mo. Montmorillonite dominates the clay residue but quartz is also present (fig. 1).

Winterset limestone, marine, Pennsylvanian. Locality, Strong's quarry, NW¼NW¼ sec. 12, T. 48 N., R. 33 W., Jackson County, Missouri. Illite and kaolinite are weakly shown with quartz in the X-ray pattern. The DTA peaks are weak but suggest kaolinite.

Alcova limestone, Triassic age. A finely crystalline, light tan specimen was collected 20 miles southeast of Lander, Wyoming, where Wyoming State Highway 8 crosses the Alcova dip slope. Quartz and illite are present, but a heavy background obscures further determination. The DTA does not add to the X-ray data.

Morrison limestone, Jurassic Age. The Morrison formation was included in this study because its non-marine origin contrasted with that of the marine limestones. Nine samples were collected from the new type section for the Morrison at the West Alameda Parkway road cut in SE¼ sec. 23, T. 4 S., R. 70 W., Jefferson County, Colorado, proposed by Waldschmidt and Le Roy (1944), whose bed numbers were also used. These limestones are commonly gray, fine-grained, and are usually somewhat earthy.

In general the differential thermograms of the Morrison samples show more intense reactions characteristic of clay minerals, *i.e.*, greater quantity of clay minerals and less quartz, than do the X-ray diffraction patterns. Perhaps these clay minerals are too finely or too poorly crystallized (or in a "degraded" crystalline state) to register clearly their crystal structures by X-ray, but they still retain characteristic strengths of chemical and crystal bonding which respond thermally. These observations accord with those of Grim, Dietz, and Bradley (1949) on recent clay sediments. Work in progress on the clay and shale layers of the same Morrison section indicates crystallinity is apparently better developed in the clay minerals of those layers than is present in the clay from the limestone. One may speculate whether recrystallization of clay minerals dispersed through limestone may not have been retarded more (since Mesozoic time) by the carbonate minerals than was their recrystallization in a clay-rich rock.

Quartz was prominent to dominant in every one of the samples tabulated below. The clay minerals are listed in order of abundance, the most abundant first.

LD-91	Illite, kaolinite (?).
LD-85	Kaolinite strongest in X-ray, illite strongest in DTA.
LD-81	Illite, diffuse kaolinite (?) band (fig. 1).
LD-77	Illite, kaolinite (both weak).
LD-73	Illite.
LD-64	Illite, kaolinite, montmorillonite, all weak but about equal intensity in X-ray patterns.
LD-62	Montmorillonite, illite, kaolinite (?).
LD-51	Illite.
LD-44	Kaolinite strongest in X-ray, illite strongest in DTA.

Peterson limestone, non-marine, lower Cretaceous. Three samples were collected from lower, middle, and upper layers of the gray, fine-grained, earthy Peterson limestone where Tin Cup River exposes the formation of the SW¼ sec. 9, T. 5 S., R. 46 E. Freedom Quadrangle, Idaho-Wyoming (Mansfield and Girty, 1927). Quartz and illite make up the clay size fraction. A diffuse faint band occupies the position where the kaolinite diffraction line would be present.

Recent Florida marl. Locality, Matacumbe Key, Florida. Although clay is scanty in this sediment a clear diffraction pattern of illite, and little quartz was obtained.

SUMMARY AND DISCUSSION

The acid insoluble residues (6N HCl), 2 microns and less in effective settling diameter, from 27 limestone and dolo-

mite samples were analyzed qualitatively for mineral determination. The ages of the rocks ranged from early Paleozoic to Recent. Both marine and non-marine limestones were studied.

Quartz is conspicuously present by occurring in most of the residues, and by being prominent in considerable quantity in many of them. It may have been carried into the limestones as tiny clastic particles, but the probability is great that a non-clastic origin, like that for the chert which is abundant in many limestones (coarse insoluble residues, McQueen, 1931; Grohskopf and McCracken, 1949) accounts for most of it. X-ray diffraction patterns of the residues run on an X-ray spectrometer show an elevated plateau of "reflection" between the 4.25 A and 3.35 A lines of quartz, whereas a pattern of pulverized lump quartz is normally low here. One wonders if this diffuse diffraction may be due to many tiny quartz particles, or to a defective quartz (?) structure arising during imperfect polymerization or recrystallization.

Illite is by far the most common clay mineral in the limestone residues. It occurs in all of the 15 samples of marine limestones and dolomites except the Bethany Falls (Pennsylvanian), and questionably in the Burlington (Mississippian). Illite occurs in all of the non-marine limestone samples examined.

Kaolinite occurs in three of the 15 marine limestones, namely, the Potosi (Cambrian) dolomite, the Burlington, and the Winterset (Pennsylvanian) limestones, and in 3 (Morrison) of the 12 non-marine samples. Additional kaolinite occurrences are doubtful.

Montmorillonite predominates in the samples of Burlington and Bethany Falls marine limestones, and is present in two of the Morrison samples. These must be considered minimum occurrences because some montmorillonite may have been lost in the acid solution treatment.

The results of this study accord closely with those of Grim, Lamar, and Bradley (1937), who likewise found illite to be the predominant clay mineral in marine limestone. Millot (1949) showed that kaolinite is generally absent in calcareous sediments, which was also confirmed by Grim (1951). The present study extends the conclusion generally to non-marine limestones, but these may include kaolinite somewhat more frequently than marine rocks. Grim (1951, p. 228) notes that there is very little montmorillonite in sediments older than the Mesozoic; montmorillonite is shown to be preserved within the Pennsylvanian Bethany Falls limestone.

Kaolinite was found by Grim, *et al.*, to be more abundant in the Mississippian and Pennsylvanian limestones than in older carbonate rocks, which is confirmed in this report. Two factors may restrict the distribution of kaolinite in marine sediments. Kaolinite which has been deposited as such may be changed to a 3-layer clay mineral during diagenesis (Grim, Dietz, and Bradley, 1949, p. 1806). Kaolinite in colloidal suspension is more readily flocculated by an electrolyte like sea water than is a 3-layer clay mineral carrying exchangeable Na or K cations. As a matter of conjecture, not tested by field observation, perhaps kaolinite may tend therefore to be deposited (flocculated) in greater proportion upon early contact with saline water, *i.e.*, near shore, or in brackish water, whereas illite and montmorillonite might move out farther. Wide spread clay partings in limestone may result from their flocculation (Keller, 1936). Basically, kaolinite has probably been formed less abundantly during geologic time than the other clay minerals simply because the prevailing weathering environments produced 3-layer minerals (Ross, 1943).

The clay minerals found in the limestones herein studied confirm the general conclusions about stability environments of clay minerals as expressed by Millot (1949) and Grim (1951).

REFERENCES

BRINDLEY, G. W., and others (1951) X-ray identification and crystal structures of clay minerals: The Mineralogical Society, London, 342 pp.

FAIRBAIRN, H. W., and others (1950–51) A cooperative investigation of precision and accuracy in chemical, spectrochemical and modal analysis of silicate rocks: U. S. Geol. Survey Bull. 980.

FAUST, GEO. T. (1940) Staining of clay minerals as a rapid means of identification in natural and beneficiated products: U. S. Bur. Mines Rept. Inv. 3522.

GRIM, RALPH E. (1951) The depositional environment of red and green shales: Jour. Sedimentary Petrology, vol. 21, pp. 226–232.

GRIM, R. E., LAMAR, J. E., and BRADLEY, W. F. (1937) The clay minerals in Illinois limestones and dolomites; Jour. Geology, vol. 45, pp. 829–843.

GROHSKOPF, JOHN G. and MCCRACKEN, EARL (1949) Insoluble residues of some Paleozoic formations of Missouri, their preparation, characteristics and application: Missouri Geol. Survey and Water Resources, Rept. Inv. no. 10.

HILLEBRAND, W. F. (1919) The analysis of silicate and carbonate rocks: U. S. Geol. Survey Bull. 700.

JACKSON, M. L., HSEUNG, Y., COREY, R. B., EVANS, E. J., VANDEN HEUVEL, R. C. (1952) Weathering sequence of clay-size minerals in soils and sediments, II. Chemical weathering of layer silicates: Proc. Soil Sci. Soc. America, vol. 16, pp. 3–6.

KELLER, W. D. (1936) Clay colloids as a cause of bedding in sedimentary rocks: Jour. Geology, vol. 44, pp. 52–59.

MCQUEEN, H. S. (1931) Insoluble residues as a guide in stratigraphic studies: Missouri Bur. Geology and Mines, 56th Bienn. Rept. State Geologist, App. 1, pp. 102–131.

MANSFIELD, G. R., and GIRTY, G. H. (1927) Geography, geology, and mineral resources of part of southeastern Idaho: U. S. Geol. Survey Prof. Paper 152, p. 104.

MEILENZ, RICHARD C., KING, MYRLE E., and SHIELTZ, N. CYRIL (1950) Staining tests, analytical data on reference clay minerals: API Research Project 49, Prelim. Rept. no. 7, Am. Petroleum Inst., New York, pp. 135–160.

MILLOT, G. (1949) Relations entre la constitution et la genèse des roches sedimentaires argileuses: Géologie Appliquée et Prospection Minière, Univ. of Nancy, vol. II.

NUTTING, P. G. (1941) The action of some aqueous solutions on clays of the montmorillonite group: U. S. Geol. Survey Prof. Paper 197, pp. 219–233.

PAGE, J. B. (1941) Unreliability of the benzidine color reaction as a test for montmorillonite: Soil Sci., vol. 51, pp. 133–140.

ROSS, CLARENCE S. (1943) Clays and soils in relation to geologic processes. Jour. Washington Acad. Sci., vol. 33, pp. 225–235.

WALDSCHMIDT, W. A., and LE ROY, L. W. (1944) Reconsideration of the Morrison formation in the type area, Jefferson County, Colorado: Geol. Soc. America Bull., vol. 55, pp. 1097–1114.

WEAVER, CHARLES EDWARD, and BATES, THOMAS F. (1951) Classification of the 2:1 minerals: Tech. Rept. no. 4, Contract No. N6onr26914NRO81-98, Pennsylvania State College.

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FIG. 1, SEPTEMBER, 1952

MINERALOGY OF SOME AUSTRALIAN DESERT SOILS

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ABSTRACT

Twenty soil profiles (78 samples) from the arid western part of New South Wales on the south-eastern edge of the Simpson Desert were examined for sand grade minerals and mechanical composition as class exercises by senior students in soil science, University of Sydney, Australia. This paper summarizes their results, and the author has interpreted the mineralogy of the soils in the light of local geology, erosion, drainage, and probable past history. A comparison is made with the true desert sands from the Simpson Desert in the center of Australia. It is found that the mineralogy of the soils reflects their geological history.

INTRODUCTION

This paper summarizes the results of mineralogical examinations of twenty soil profiles (78 samples) made by senior students in soil science, School of Agriculture, University of Sydney, Australia, in the years 1949, 1950, and 1951. The work was done under the writer's direction. All mineralogical identifications have been checked by the writer who is also responsible for the detailed descriptions of the minerals and for the interpretation of the findings.

The soil profiles were sampled during field trips by Dr. E. G. Hallsworth in the arid western part of New South Wales (fig. 1). The area is on the south-eastern edge of the Simpson Desert which occupies the center of Australia. The Simpson Desert has been described by Madigan (1938, 1939, 1946); the soils of the Simpson Desert have been described by Crocker (1946) and the sands by Carroll (1944). The area from which these soil profiles were collected has not been described in detail, but various geological reports of a reconnaissance nature have been summarized by David (1950).

Inasmuch as the whole internal desert area of central Australia can be considered as a single unit which has been subjected to fluctuations of climate since the Cretaceous period, the arid western part of New South Wales is part of this unit. The desert as a whole originated as the seat and surroundings of an internal drainage system which became desiccated during an arid epoch at the beginning of Recent time (Crocker, 1946; Eardley, 1948), when extensive parallel dunes of bright red sand were formed. Tertiary and Cretaceous beds probably contributed most of the sand (Carroll, 1944; Crocker, 1946), but Pliocene laterization has been recognized as an important influence (Whitehouse, 1940). Figure 1 indicates that the soils described here occur associated with a ridge of pre-Cambrian rocks which forms a low divide between a westerly drainage and part of the Darling River drainage system. In part the soils are similar to the red desert sands; others are from isolated dunes, flat sands, accumulations of sand showing reticulate pattern or from stony gilgai soils (gilgai = crab-hole or melon-hole).

DETAILS OF THE SOILS

The soils are nearly all red sands which have been placed by Prescott (1931) in his Desert Sand and Loam group of soils. Details of the profiles are given in table 1, and their approximate positions can be seen on figure 1.

The profiles can be grouped as follows:

Group 1—from the western side of the

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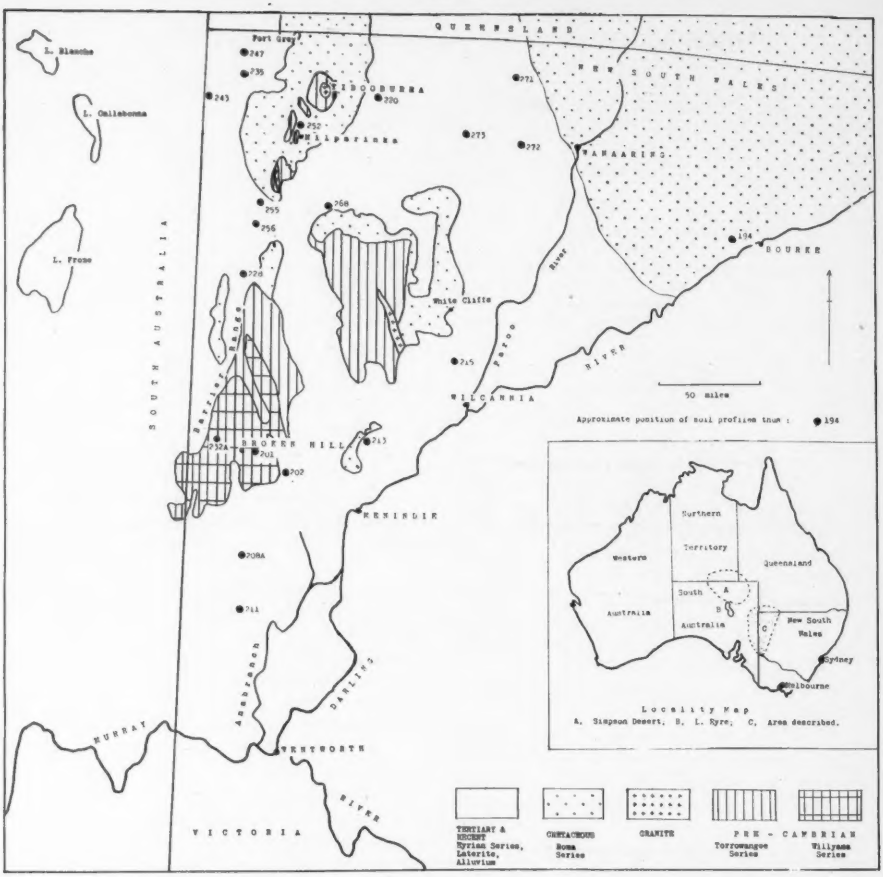

FIG. 1.—Map of the area described showing positions of soil profiles with respect to geology and drainage (geology modified from David's Geological Map of the Commonwealth of Australia, 1950).

Barrier Ranges in an area with westerly drainage and having parallel sand ridges somewhat similar to those of the Simpson Desert. Nos. 228, 232A, 235, 243, 247, 252, 255, and 256 belong here.

Group 2—from the eastern side of the Barrier Ranges and forming part of the internal drainage area of the Bulloo, Paroo, and Warrego Rivers. The area is probably underlain by Tertiary and Cretaceous sediments. Nos. 194, 220, 268, 271, 272, and 273 are from this area.

Group 3—situated south-east of the Broken Hill part of the Barrier Ranges in the drainage basin of the Darling River and its anabranches. Nos. 201, 202, 208A, 211, 213, and 215 are in this area.

The principal rocks cropping out in the areas from which the soils were collected are shown in figure 1. The oldest are the pre-Cambrian Willyama

TABLE 1.—*Localities and depths of samples*

Profile No.	Locality	Depth from which samples were examined (inches)
194[1]	20 miles west of Bourke on Bourke-Wanaaring road	3–6; 12–18
201	11 miles from Broken Hill on Menindie road	0–3; 36–42
202	4 miles from Stephen's Creek on Broken Hill-Menindie road	0–1; 6–9; 9–12; 12–18; 60–72; 72–84
208A	55 miles south of Broken Hill on Wentworth road	0–1; 1–3; 3–6; 24–36; 36–48; 60–72
211	77 miles south of Broken Hill on Wentworth road	1–3; 24–48
213	65 miles from Broken Hill on Wilcannia road	1–3; 36–60
215	22 miles north-west of Wilcannia on White Cliffs road	½–3; 24–36
220	44 miles from Tibooburra on Conulpie road	½–3; 36–48
228	North of Corona, on Pine View road	0–½; 36–48
232A	West of Broken Hill below Quinjambi station	0–½; 1–3; 6–12; 24–36; 48–60; 60–72
235	Waka road, south of Fort Grey	0–½; 24–36
243	White Catch, South Australian border due west of Tibooburra	3–6; 60–72
247	Waka road, Fort Grey	0–½; 24–36
252	Near Milparinka, Tibooburra road	0–½; 3–6; 6–12; 12–24; 24–30; 36–48; 60–72
255	Sanpah, Pine View road, Pine View	0–½; ½–1; 6–12; 24–36; 48–60; 60–72
256	50 miles south of Tibooburra, between Pine View and Sanpah	0–½; ½–1; 3–6; 18–24; 48–60; 60–72
268	Wonominta turnoff, Tibooburra-Broken Hill road	0–½; 36–48
271	Thurloo Downs, about 50 miles north-west of Wanaaring	0–½; 6–12
272	30 miles west of Wanaaring	0–½; 3–6
273	Wanaaring, Bourke road	0–½; ½–1; 6–12; 24–36; 36–48; 48–60

[1] Numbers refer to the soil collection, School of Agriculture, University of Sydney.

series (schists, gneisses, intrusive granites, augen-gneisses, and gabbro), overlying which is the Torrowangee series (quartzites, limestone, flaggy sandstones, and shales). Overlying the pre-Cambrian rocks are the Cretaceous beds forming part of the Great Artesian Basin (Tambo and Roma series of sandstones and shales). Remnants of dissected Tertiary sediments occur in the vicinity of Tibooburra and elsewhere in the form of mesas; they extend southward for many miles and eastward to about as far as Bourke (David, 1950). The Tertiary rocks are believed to have been almost entirely covered by a laterite capping which developed during the Pliocene (Whitehouse, 1940). This capping has also been subjected to arid erosion and material from it probably has been incorporated, together with disintegrating Tertiary and Cretaceous materials, in the present sandy soils.

The grading and sorting of the sands will be reported elsewhere, but there are several features of interest from a mineralogical point of view. The maximum grade for the sands generally falls in the 0.5–0.25 mm diameter class, but it was found that sub-surface samples were finer with the maximum in the 0.25–0.12 mm grade. The sub-surface sands are very similar in grading to those of the Simpson Desert (Carroll, 1944). The sorting of these sands is much less perfect than those of the Simpson Desert, and the maxima only reach 40–50 per cent, except at the surface where the maxima are 60–70 per cent. A few soils with a notable clay content were included in this series.

METHOD OF EXAMINATION

Representative samples of the sands

were sieved through a set of sieves giving approximately the Wentworth scale of grades (Wentworth, 1922). The size next finer than the maximum grade was selected for mineralogical examination, as this grade has proved to yield a representative suite of heavy minerals; thus if the maximum is in the 0.25–0.12 mm grade then a separation was made of the 0.12–0.06 mm grade. The red coloring matter, which is present as a thin skin of hematite around each grain, was removed by boiling in 1:1 HCl for a few minutes. About 10 gm of sample was dried, weighed, and placed in bromoform (sp. gr. 2.8+) to obtain the heavy residue; this was weighed and tested with a magnet before mounting for microscopic examination. The mineral grains were identified optically, and estimates of the frequency of the various heavy minerals made by counting up to 300 non-magnetic grains. Owing to the fact that numerous people contributed to these estimations, no percentage figures are given in table 2 in which the mineralogical data are assembled.

MINERALOGY

Heavy Residues

The amount of heavy residue, by weight in the grade separated, ranges between one-half and two per cent, with an average of about three-quarters per cent. It is noticeable that the greatest quantity of heavy residue occurs in the surface samples.

The following minerals were recorded: magnetite, ilmenite, leucoxene (listed as opaques), tourmaline, zircon, rutile, andalusite, garnet, kyanite, sillimanite, staurolite, amphibole, epidote, zoisite, monazite, spinel, corundum, sphene (titanite).

Table 2 gives the mineralogy of the soils, grouped as detailed earlier. It will be seen that the number of different heavy minerals ranges from five to twelve. Those profiles containing only five to eight species can be regarded as impoverished. Leaving the opaque grains out of consideration, the other minerals common to all the residues are tourmaline and zircon, with rutile and staurolite present in all but one or two profiles. It is noteworthy that whereas tourmaline is fairly abundant in the soils, zircon is not plentiful, a reversal of what is very often found for these two minerals. Rutile is likewise somewhat scarce. The metamorphic minerals are strongly represented, with staurolite the most abundant, followed by sillimanite, garnet, kyanite, and andalusite, in that order. The rocks of part of the area, particularly the early pre-Cambrian Willyama series, contain all these metamorphic minerals, sometimes in segregations as, for example, sillimanite, or sillimanite and kyanite, as at Thackaringa about twenty miles west of Broken Hill (profile 201 was collected near here and shows an enrichment in sillimanite). The remaining minerals listed are of sporadic occurrence. The residues are very similar to those found in the Simpson Desert sands (Carroll, 1944).

Notes on the individual minerals—The *opaque grains*, consisting of magnetite, ilmenite, and leucoxene, make up the bulk of the heavy residues of all these samples with the exception of profile no. 201, where garnet is very plentiful, and no. 202, where sillimanite predominates.

Magnetite, in quantities from a trace to about one-tenth of the heavy residue, is present in all the samples. The remaining black grains were identified as *ilmenite*, which makes up from about half to three-quarters of the remaining part of the residues.

Leucoxene, in silvery cream-colored grains, was nearly always present in various amounts.

Tourmaline. Although tourmaline is constantly present in these residues, it does not occur in large amounts. In general, the grains are somewhat worn to well-rounded and spherical; they range in color from brown and brownish green to gray, with odd blue grains. In one profile (no. 255), there are parti-colored blue and brown grains. In no. 202 the grains are in small sharp-edged, unworn prisms which indicate a nearness to source.

TABLE 2.—*Mineralogy of the soils*

Profile No.	Group 1								Group 2						Group 3					
	228	232A	235	243	247	252	255	256	194	220	268	271	272	273	201	202	208A	211	213	215
Heavy minerals																				
Opaques[1]	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Tourmaline	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Zircon	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	+	+	+	+
Rutile	−	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Andalusite	+	+	−	−	−	+	+	+	+	−	−	−	−	+	+	−	+	−	+	−
Garnet	−	+	+	−	−	+	+	+	−	−	−	+	−	−	A	+	+	−	+	−
Kyanite	−	+	+	−	+	+	+	−	+	−	−	+	−	+	+	−	+	+	+	−
Sillimanite	+	+	−	+	−	+	+	+	−	−	+	+	−	+	+	A	+	+	+	+
Staurolite	+	+	+	+	+	+	+	+	+	+	+	+	−	+	+	+	+	+	+	+
Amphibole	−	+	−	−	−	+	−	+	−	−	+	−	−	−	+	+	+	+	−	+
Epidote	−	+	−	−	−	−	+	+	−	−	−	−	−	−	+	−	−	+	+	−
Zoisite	−	−	−	−	+	−	−	+	−	−	−	−	−	−	−	−	+	−	−	−
Monazite	−	+	−	−	−	+	+	−	−	−	−	−	+	+	+	−	+	−	−	−
Spinel	+	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	−	+	−	−
Corundum	+	−	−	−	−	−	−	−	+	−	−	−	−	−	−	−	−	−	−	−
Sphene	−	−	−	−	+	+	−	−	−	−	−	−	+	−	−	−	−	−	−	−
Number	8	12	7	5	8	12	11	11	8	5	7	8	6	9	12	7	12	10	10	7
Light Fraction																				
Quartz	A	+	A	A	A	+	A	A	A	A	+	A	+	A	A	+	+	A	A	A
Orthoclase	−	−	−	−	−	−	−	−	−	−	+	−	+	−	−	−	−	−	−	−
Microcline	−	−	−	−	−	−	+	+	−	−	−	−	−	+	+	−	−	−	−	−
Microperthite	−	−	−	+	+	−	−	−	−	+	−	−	−	−	−	−	−	−	+	+

[1] Opaques include ilmenite and leucoxene; magnetite was removed prior to mounting. A=abundant; +=present, −=absent.

Group 1, western side of the Barrier Ranges; Group 2, east of the Barrier Ranges in drainage basin of the Bulloo, Paroo Rivers; Group 3, south-east of the Barrier Ranges in drainage basin of the Darling River.

Zircon is not an abundant mineral in these samples. It is present as small, colorless, worn to well-rounded grains the surfaces of which are occasionally polished as in no. 228. In no. 255 one or two acicular unworn zircons were found accompanying the rounded grains. The rounding of the zircon suggests a long abrasional history, with a probable original source in the pre-Cambrian metasediments. There is no zircon except the fresh grains in no. 255, which it is thought could have come directly from granitic rocks. The zircon is colorless and has inclusions, but no zoning.

Rutile is a minor constituent of nearly all the residues. It is in small deep reddish-brown, worn, prismatic grains. Somewhat less worn grains occur in no. 202. Worn yellow-brown rutile is found in no. 252. The rutile is not associated with anatase, but, as noted above, leucoxene is nearly always present.

The metamorphic minerals—these will be described in the following groups:

1. Andalusite, kyanite, and sillimanite.
2. Garnet and staurolite.
3. Amphiboles, epidote, and zoisite.
4. Spinel and corundum.

The pre-Cambrian rocks of the Barrier Ranges are rich in groups 1, 2, and 3, and it is therefore assumed that these minerals came from this source.

1. *Andalusite, kyanite, and sillimanite.* *Sillimanite* is the most plentiful of these, and is present in fifteen of the profiles. It occurs as fresh prismatic grains in nos. 201, 202, 228, and 232A; and as worn grains in 211, 213, 215, 243, 252, 255, 271. It is the most abundant mineral in the residue of no. 213, on the Wilcannia road. It is likely that the fresh sillimanite, occurring as it does in those samples which yield a large variety of heavy minerals, has been derived from the source rocks much more recently than worn sillimanite which has probably been incorporated in sedimentary rocks (Cretaceous and/or Tertiary) and then released to the present day sands and soils. *Kyanite* is present in twelve of the profiles. It is in typical worn grains in small quantity, and is never a very conspicuous member of the residues, as is sillimanite. No pleochroic grains were found. *Andalusite* is present in ten of the profiles, but is much less plentiful than kyanite. It is in worn colorless grains, some of which are pleochroic; other grains contain carbonaceous inclusions (chiastolite).

2. *Garnet and staurolite.* Both these minerals are conspicuous in certain of the suites, staurolite being present in nineteen of the profiles, and garnet in ten only. *Garnet.* When it is present in a heavy residue of this set of samples it tends to be very conspicuous, and may be the most abundant non-opaque mineral. It is colorless to pale pink, and is in angular grains often with pitted or etched surfaces. Garnet is accompanied by other angular grains such as staurolite and sillimanite, and even when the other grains in an assemblage are somewhat worn it remains angular, as in no. 213. In only one profile, no. 220, does the garnet show wear, and then the only other non-opaque minerals are zircon, staurolite, rutile, and tourmaline, all well worn. From these observations, and from those on sediments elsewhere, it seems that garnet tends to be more "short-lived" than the other metamorphic minerals, and may be abundant only near its source. Moreover it does not become rounded easily. *Staurolite* is in typical, somewhat massive, prismatic grains with strong pleochroism. The grains are angular in nos. 201, 202, 228, 232A, 252, and 268; and worn in 208A, 211, 213, 215, 220, 243, 247, 255, 256, 271, and 273. It is probable that the derivation of staurolite follows that of sillimanite.

3. *Amphiboles, epidote, and zoisite.* These are somewhat minor constituents. The *amphibole* is the blue-green metamorphic type with a small extinction angle; the grains all show wear. Amphibole is present in nine profiles, but in small amount. A little glaucophane was found in no. 202. *Epidote* is more plentiful than *zoisite:* the former occurs in six profiles,

the latter in three. Epidote is in typical pale yellow-green grains, often rather massive, and generally showing wear. Zoisite is present as odd grains only and shows typical features.

4. *Spinel and corundum.* Both these minerals accompany the metamorphic minerals here as elsewhere. The *spinel* is the dark green variety, pleonaste, and no grains of a pale green variety, suspected to be gahnite, were seen. The spinel grains are well-rounded with smooth surfaces. The *corundum* is in worn patchy blue grains. It accompanies spinel in no. 228, but was only recorded as a very few grains throughout all the samples examined.

The remaining heavy minerals are *monazite* and *sphene*, neither abundant. Typical pale green rounded grains of monazite occur in eight of the profiles in small quantity. Sphene is present only in three profiles where it displays its typical form: it is rather angular in very pale yellow-brown grains.

The Light Fraction

Quartz is the principal constituent of most of these samples except the soils with higher clay content. The grains generally are not particularly well-rounded, and do not show many features of interest. They are similar to those described from the Simpson Desert (Carroll, 1944). In no. 228 some of the grains show re-growths such as are commonly found in the quartz of sandstones, and this can be taken as evidence of derivation from sedimentary rocks. Small, unusually well-rounded grains occur in no. 271, which is also probably derived from sediments. In nos. 202, 208A, 232A, and 252 the amount of quartz is reduced because of the large clay content.

Feldspar. Orthoclase, microcline, and microperthite were identified in the various profiles as shown in table 2. Feldspar is never plentiful, and only in two profiles, nos. 268 and 272, is orthoclase at all conspicuous in amount; here it may make up about one-quarter of the light fraction. Small grains of microcline, and of microperthite, a feldspar characteristic of gneisses, are found in a number of the profiles, but on the whole the feldspar content of the sands is very low.

ORIGIN OF THE SOILS

Evidence of the Heavy Residues

An examination of table 2 shows that, as mentioned above, some of the heavy residues contain very few mineral species. This information may be summarized thus:

	Impoverished suites 5–8 minerals	Enriched suites 9 or more minerals	Total no.
Group 1			
No of profiles	4	4	8
Group 2			
No of profiles	5	1	6
Group 3			
No of profiles	2	4	6
Totals:	11	9	20

The distribution of the impoverished suites (in profiles 194, 202, 215, 220, 228, 235, 243, 247, 268, 271, 272) is shown in figure 1 from which it can be seen that they are all situated some distance from outcrops of pre-Cambrian rocks in situations where derivation from later sedimentary rocks appears likely. Their field distribution, coupled with the worn appearance of the actual grains, confirms the belief they originated from the disintegration of some sedimentary series such as occurs in the Cretaceous or Tertiary. The fact that there was a Pliocene laterization does not invalidate their origin in sediments which may have been laterized.

The enriched suites, on the other hand, are, with few exceptions, closely associated with outcrops of pre-Cambrian metamorphics which are able to supply fresh garnet, staurolite, sillimanite, as well as andalusite, kyanite, tourmaline, amphibole, epidote, and zoisite. The angular appearance of such minerals as garnet, sillimanite, and

staurolite, and in one profile, of tourmaline, together with their abundance and generally robust and rugged appearance testify to a later origin, or rather, to a later incorporation in the sands than the worn grains of these same minerals which constitute part of the improverished suites. This area, therefore, provides a good example of erosion and deposition in a more or less closed basin. The Barrier Range area (fig. 1) and its extensions were eroded in Cretaceous and Tertiary times, and the materials deposited in lake systems to form sandstones and shales of the Tambo and Roma series (Cretaceous), and, possibly by partial re-working, the Eyrean sediments (Tertiary). After draining of the lakes by uplift and infilling, the sediments were subjected to erosion, but, because of an arid period, coupled with a slight internal drainage such as obtains in a desert environment, the materials were not moved out of the basin. Some mineral species disappeared, such as garnet, andalusite, amphibole, epidote, and zoisite, and impoverished suites are found in these sands today. The few grains of these minerals which are present, show, together with the generally worn appearance, that the sandstones and shales originally contained much more of them. The sand ridges of the Simpson Desert and its surroundings were developed during this arid period. Subsequently there was a wetter period during which further weathering and erosion took place, and the pre-Cambrian metamorphics were drawn upon to supply additional material. Those profiles collected near the newly weathered pre-Cambrian rocks contain enriched suites of minerals, often with abundant fresh, angular garnet, sillimanite, and staurolite. That even these sands are of some geological antiquity is indicated by the worn appearance of such minerals as andalusite and kyanite, which are "softer" and do not "stand up" as well as staurolite and sillimanite to long-continued weathering in soils and sediments.

For this particular area the appearance of the various mineral grains in any profile can be interpreted as shown in the tabulation below.

Evidence of the Light Fractions

Table 2 shows that quartz is the predominating mineral of this fraction, but from its presence alone very little information as to the origin of the sands can be obtained. The grading of the sands is

Tourmaline	Worn appearance and derived from earlier sediments.
Zircon and Rutile	Mostly mechanical abrasion, but small zircons may be derived directly from pre-Cambrian metamorphics.
Andalusite	Worn appearance probably due to solubility and removal in sediments; mechanical abrasion probably slight.
Garnet	Fresh and angular grains near source; pitted surfaces indicate lengthy period in a moist environment; seldom rounded and tends to be lost from sands and sediments.
Kyanite	Worn appearance probably indicates that some alteration takes place under moist conditions; it is only angular near source.
Sillimanite	Resistant to abrasion and chemical action; apparently becomes slightly rounded when aged.
Staurolite	Similar in appearance to sillimanite, but the presence of inclusions allows more weathering to take place.
Amphibole	Grains only angular near source; become rounded and eventually disappear when aged.
Epidote and Zoisite	Abundant and angular only near source; epidote is more resistant than zoisite or than amphibole.
Monazite	Persists as detrital grains for a long time, generally rounded.
Spinel	Very resistant and apparently survives several sedimentation cycles.
Corundum	Very resistant to weathering and abrasion.
Sphene	Persists in sediments for a long time.

important, but this will be described and discussed by others elsewhere. It can be said, however, that the grading suggests an origin largely from sedimentary rocks, even though the grading has probably been modified by wind action, and possible accumulation of alluvial material. Laterization apparently does little to disturb the original grading of sands. The presence of feldspar in some of the profiles indicates that humid conditions did not entirely destroy this mineral, though its scarceness may also be attributed to the laterization which took place during the Pliocene. It is noteworthy that microcline and microperthite, which are more resistant varieties of feldspar than orthoclase, were recorded from more profiles than orthoclase.

CONCLUSIONS

The examination of a number of sand fractions of soils from this arid part of Australia has given an interesting illustration of what has occurred over considerable periods of time when one main source for detrital material has been drawn upon to supply sedimentary rocks which have since been weathered and eroded to give the present day sands and sandy soils. A feature of importance from the soils point of view is the scarcity in the sands of reserves of weatherable minerals such as feldspars and ferromagnesians. Only in nos. 268 and 272 are there appreciable amounts of orthoclase feldspar; where feldspars are present in other profiles they are found to be microcline and microperthite, which are much more resistant to weathering. There are only minor quantities of ferromagnesians in any of the profiles. The mineralogical difference between newly derived sands from the precambrian rocks and those sands which have probably undergone sedimentation, laterization (with its intense leaching), and erosion, indicates that there is here fairly good evidence of an order of weatherability of the heavy detrital minerals.

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REFERENCES

CARROLL, DOROTHY (1944) The Simpson Desert Expedition, 1939. Scientific Reports: No. 2, Geology, Desert Sands. Trans. Royal Soc. South Australia, vol. 68, pp. 49–59.

CROCKER, R. L. (1946) The Simpson Desert Expedition, 1939, scientific reports, no. 8, the soils and vegetation of the Simpson Desert: Trans. Royal Soc. South Australia, vol. 70, pp. 235–258.

DAVID, T. W. E. (1950) Geology of the Commonwealth of Australia. Arnold, London.

EARDLEY, C. M. (1948) The Simpson Desert Expedition, 1939, scientific reports, no. 7, Botany, pt. ii. The phytogeography of some important sand-ridge deserts compared with that of the Simpson Desert: Trans. Royal Soc. South Australia, vol. 72, pp. 1–29.

MADIGAN, C. T. (1938) The Simpson Desert and its borders: Jour. Royal Soc. New South Wales, vol. 59, pp. 503–535.

——— (1945) The Simpson Desert Expedition, 1939, scientific reports, introduction, narrative, physiography, and meteorology: Trans. Royal Soc. South Australia, vol. 69, pp. 118–139.

——— (1946) The Simpson Desert Expedition, 1939, scientific reports, no. 6, Geology, the sand formations: Trans. Royal Soc. South Australia, vol. 70, pp. 45–66.

PRESCOTT, J. A. (1931) The soils of Australia in relation to vegetation and climate: Council Sci. & Ind. Research (Australia), Bull. 52.

WENTWORTH, C. K. (1922) A scale of grade and class terms for clastic sediments: Jour. Geology, vol. 30, pp. 377–392.

WHITEHOUSE, F. W. (1940) Studies in the late geological history of Queensland: Univ. of Queensland Papers, vol. 2 (n.s.), no. 1, pp. 2–22.

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FIGS. 1–8, SEPTEMBER, 1952

FATHOGRAM INDICATIONS OF BOTTOM MATERIALS IN LAKE MICHIGAN

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ABSTRACT

Fathograms recorded by a commercial sonic sounding apparatus used in a study of the bottom sediments of Lake Michigan show characteristic traces for sand, till, and clay bottom. Multiple traces obtained in some areas were correlated with specific clay strata. The effects of rough water, and of variation of signal strength are illustrated, and reflections from objects in the water, probably fish, localized in relation to the thermocline, are noted.

INTRODUCTION

Fathograms, the records of the depth of water plotted by recording sonic sounding apparatus, have been obtained by a number of vessels during the past several years. Study of these records from areas where the nature of the bottom materials is known has shown that different bottoms give different returns: a smooth hard bottom returns a relatively large percentage of the energy sent out by the sounding apparatus, while a soft bottom returns a relatively small percentage of energy. There has been some recognition by submarine geologists and hydrographers that the sharpness or fuzziness of the recorded bottom profile was related to the kind of material on the bottom.

The effect of bottom materials on reflection of underwater sound, used in submarine detection, is well known to those who have been concerned with this field since early in World War II (Russell, 1950). A smooth sand bottom gives little distortion in reflecting the sound beam, whereas a hard, rough bottom, such as rock, scatters so much sound back to an echo-ranging ship that the target echo may be masked.

Dual traces have been obtained with a recording fathometer over some bottoms, and these have been interpreted as representing a layer of softer sediment overlying a harder substratum (Murray, 1947).

It is the writer's opinion that the full capabilities of the recording fathometer have not been used in most marine work. Even on vessels engaged in oceanographic study the fathometer generally is employed merely to give an indication of the depth of the water.

During a two-weeks cruise on Lake Michigan in the summer of 1951 the writer found a high degree of correlation between the appearance of the bottom trace on the fathogram and the nature of the bottom material. Several portions of fathograms are reproduced in the following pages, along with a description of the bottom samples obtained in the areas covered. The purpose of the present paper is to illustrate the fathogram indications of bottom material. Discussion of the significance of the bottom materials and their geological relationships will be presented elsewhere.

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Silverman and Mr. Raymond F. McAllister, graduate students, University of Illinois, assisted ably in the field. Mr. L. W. Hough made the photographic reproductions of the fathograms.

SOURCE OF INFORMATION

The information presented here was obtained as a part of a study made under an Office of Naval Research-University of Illinois project. During the summer of 1950 a few long core samples were collected from deep water in Lake Michigan, from the U. S. Coast Guard buoy tender *Woodbine* which carried adequate rigging to handle a 70-foot long piston type coring tube. These samples provided information on the bottom materials, but no usable fathograms were obtained since the sounding apparatus gave a very faint recorded trace and it was not tended as a routine part of the work. During a 14-day period in the summer of 1951 a sampling and sounding program was carried out on board the U. S. Fish and Wildlife Service research vessel *Cisco*. During the cruise a total of 126 bottom-sampling stations was made, and the recording fathometer was operated almost constantly when the vessel was under way.

The fathograms were made with a standard commercial apparatus, built by the Submarine Signal Division, Raytheon Manufacturing Co., which uses chart 15 AT-A or chart 383–1003Pl. The fathometer employs two depth scales; "shallow," 0 to 100 fathoms, and "deep," 100–200 fathoms. (A fathom equals six feet.)

This apparatus has no separate visual depth indicator, and all soundings must be read from the fathogram paper. It probably was because of this necessity that unusual attention was given to the recorded trace at the start of the cruise. It was found that by frequent adjustment of the power output of the fathometer a trace of the bottom profile could be obtained which had nearly uniform density, or that dual or multiple traces of the bottom could be obtained, in certain areas of the Lake, by increasing the power output.

It should be emphasized that a recording fathometer, suitable for depth range to be covered, must be kept in good operating condition and its power output must be adjusted frequently, if the fathograms are to be of use in the study of bottom materials.

TYPICAL FATHOGRAMS

Preliminary Discussion

The fathograms shown in figures 1–8 were reproduced photographically from portions of the long paper rolls taken from the fathometer. When the vessel was stopped, a vertical black line was marked on the record, another line was marked when the sampling apparatus reached bottom, and a third line was marked when the vessel resumed its course, as shown in figure 5. In all of the other figures the paper roll has been folded so that the depth recording made while the vessel was stopped is hidden.

The depth scale in all the figures except 4 and 5 should be read as it appears; 0 to 100 fathoms. In figures 4 and 5, 100 fathoms should be added to the scale shown because the fathometer was operating on its "deep" scale when these recordings were made. The absence of a horizontal black line recorded at the top of the scale indicates that the fathometer was operating on the deep scale.

All of the fathograms except figure 7 were made under calm conditions with the vessel operating at a cruising speed of 10.5 miles per hour. The fathogram of figure 7 was made in a rough sea with the vessel operating at reduced speed.

Secondary reflections from a single bottom interface are shown in several of the figures (1, 2, 3, 8). These are readily recognized because they occur at twice the depth of the uppermost reflection; they represent a pickup of sound which has travelled from ship to bottom, bottom to surface, surface to bottom, and bottom to ship, or approximately twice as far as did the first signal re-

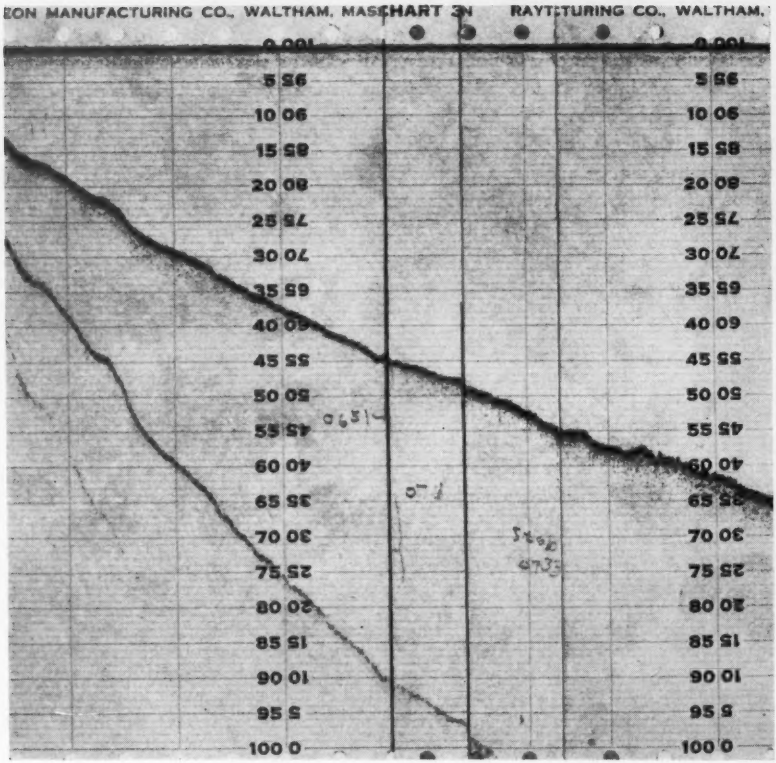

FIG. 1.—Center portion shows typical sand bottom trace, a relatively thin, clear-cut line; right center portion shows slightly fuzzy line made by reflection from a clayey sand.

ceived. There is a faint record of a third pickup in figure 1, where a part of the sound made the round trip from surface to bottom to surface a third time. These secondary reflections generally may be ignored in the interpretation of fathograms.

Sand Bottom

Figure 1 shows, in the middle portion of the bottom profile, at depths of 40 to 50 fathoms, the typical appearance of a fathogram taken over a firm sand bottom. The line of the profile is relatively thin and dark, and there are practically no feather edges or no fuzziness shown. Bottom samples taken on this profile, at the left and center vertical black lines (depths, 44 and 48 fathoms) contained well-sorted fine sand. A bottom sample taken at the right-hand vertical black line (depth, 55 fathoms) contained a poorly sorted clayey sand. Here the fathogram shows a slight but distinct fuzziness on its bottom side.

Figure 2 shows the typical sand bottom trace in its center portion. A bottom core sample 30 inches long was taken at the

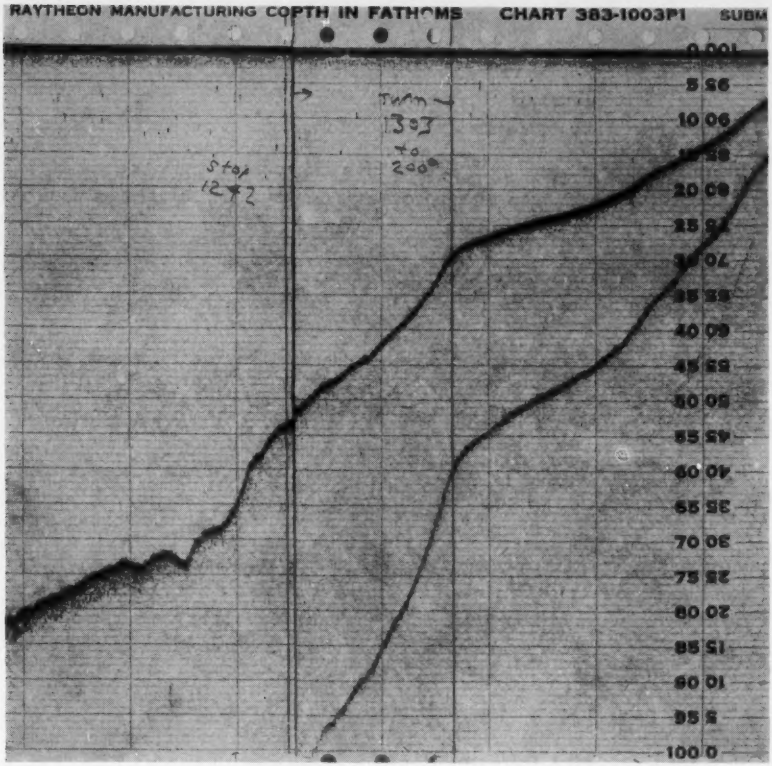

FIG. 2.—Typical sand bottom trace appears in center portion of profile.

position of the vertical black line, left center, in a depth of 53 fathoms. Some stratification was visible in the core sample, but all of the sand was well- to moderately well-sorted, and ranged from coarse to fine in size.

Till Bottom

Figure 3 shows a trace taken over till bottom. The till in this area is the red Valders (Wisconsin) till, with a compact sandy clay matrix dominating but with abundant pebbles. Generally, in this portion of the lake, there is a thin veneer of sand and there are some pebbles scattered over the surface of the till. On the steep slope, at the left hand vertical black line in figure 3, no samples were recovered by either a coring tube or a Peterson type clam-shell bucket. It is possible that bed rock crops out on this steep slope. Till was found in shallower water to the right (east) of this slope, a short distance away. A core sample taken at the position of the center vertical black line (right center of figure 3) contained a pebble overlying tough pinkish gray till. At the position of the right-hand vertical black line, no core sample

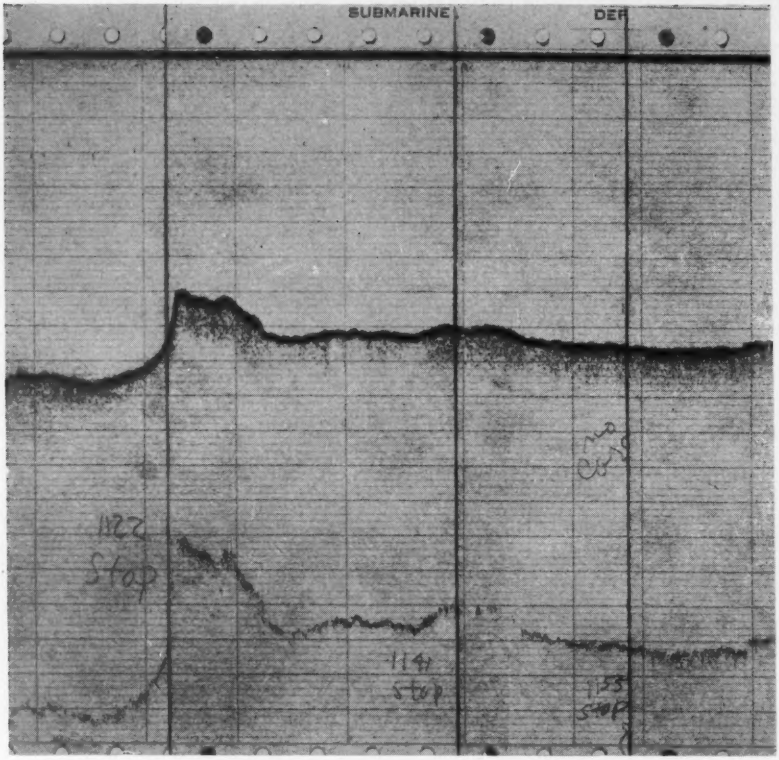

FIG. 3.—Till bottom trace; upper side of profile is well-defined, underside is fuzzy.

was obtained but the coring tube entered the bottom a short distance and stuck so firmly that the winch was stalled when the first attempt was made to retrieve the apparatus. This, and a smear of reddish-gray gritty clay on the outside of the coring tube, suggested till bottom.

Figure 4, a profile with depths ranging from 100 to 133 fathoms, shows two peaks with a typical till trace, whereas the adjacent deeper portions of the profile show dual or multiple traces. A core sample taken on top of the left-hand peak contained a pebbly and sandy tough red clay till.

Clay Bottom

Before the fathograms of this type of bottom are discussed, it is desirable to describe the clay sediment types and their distribution in Lake Michigan. The longest core samples from the lake were collected in 1950, without obtaining fathograms of the areas sampled. These long cores, supported by several dozen shorter ones collected the following summer, when fathograms were obtained, provide a consistent picture of the deep-water sediments of the Lake.

In general, in the central third of the

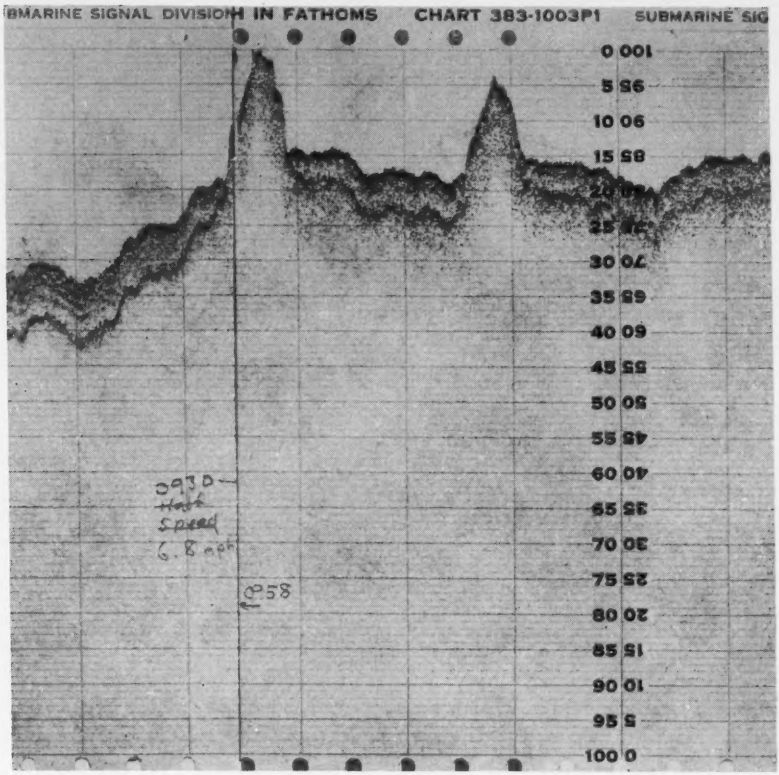

FIG. 4.—Till bottom trace on two high points; clay bottom traces in adjacent deeper water. Add 100 fathoms to depth scale.

lake, in all topographic basins with a depth greater than 60 fathoms, the bottom has the following composition, from the surface downward; dark gray lake clay with high water content, grading to light gray lake clay with moderately high water content, grading sharply to red lake clay with relatively low water content; in some places the lower part of the red clay contains silt laminae (it is varved). Wherever the red clay was penetrated a red till was found. This complete section was found in a core 35 feet long, taken from the deepest point in the lake (154 fathoms). All of the shorter cores taken in deep basins contained soft gray clay, and many of them extended downward into the stiffer red clay.

On topographic high points, even in deep water, the gray clay generally is absent, and the entire lake clay sequence is missing from some deep ridges, leaving till exposed (as in figure 4). Core samples from some of the ridges and basin margins, at great or intermediate depths, have a few feet of the relatively stiff red lake clay overlying glacial till.

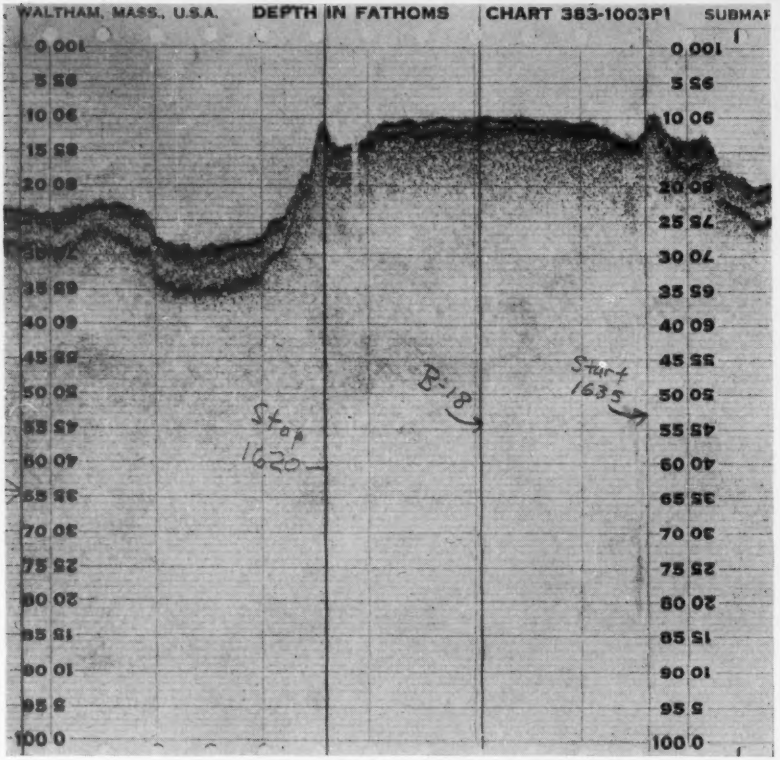

FIG. 5.—Clay bottom traces. The three traces at left of center represent soft gray clay, stiffer red clay, and, probably, glacial till. The two traces in center portion represent red clay over a substratum, probably glacial till. Add 100 fathoms to depth scale.

Three principal reflecting horizons in the lake bottom may be expected, from the above summary of sediment types: (1) the top of the soft gray clay; (2) the top of the stiffer red clay; (3) the top of the stiff till. The lower portions of the red clay have not been sampled adequately in the deep basin areas, but there may be lithologic boundaries within the red clay which are sufficiently well defined to give additional reflecting horizons in those areas.

Figure 5 shows a bottom profile with three distinct traces in its deeper portions (120 to 130 fathoms), and two distinct traces in its shallower portion (110 fathoms). A core sample taken at the left edge of the figure contained six feet of soft gray clay overlying red clay. Presumably the upper trace at this point is from the top of the gray clay, the next lower trace is from the top of the red clay, and the third, or lowest, trace is from the top of till which generally underlies the red clay. A core sample taken from the shallowest point on the profile of figure 5, at the line marked B-18, contained six feet of red clay. Here, the top

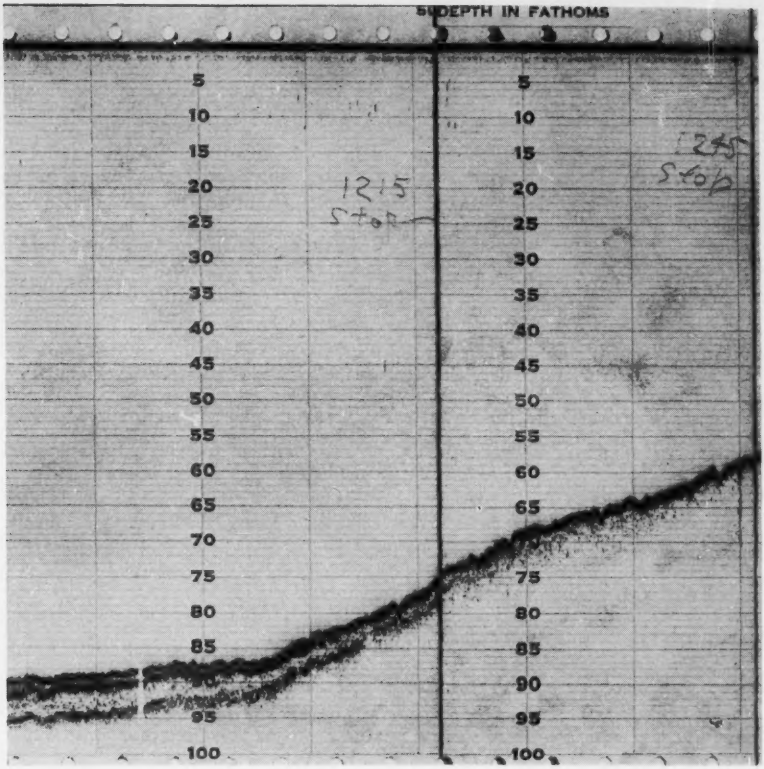

FIG. 6.—Three distinct traces at left represent gray clay, red clay, and a third material, probably till, at bottom. The gray clay pinches out and red clay comes to the surface in center portion of figure.

trace is from the top of the red clay and the other, lower, trace presumably is from till.

Figure 6 shows three distinct traces in its left-hand portion; the middle trace of these three comes to the surface in the middle portion of the figure, where there are only two traces; in the right-hand portion of the figure there is only one distinct trace. A small sample taken a short distance to the left of the profile shown in figure 6 contained gray clay. A core sample taken at the vertical black line near the center of the figure consisted of nine feet of unlaminated red clay, most of which was of normal consistency, but toward the bottom of the core the clay became more compact. A core sample taken at the right edge of the figure contained nine feet of very stiff red clay with compact silt laminae. Farther to the right, a short distance beyond the edge of the figure, till bottom was found. This figure is interpreted as representing, at its left, three reflecting horizons consisting of: (1) top of the gray clay; (2) top

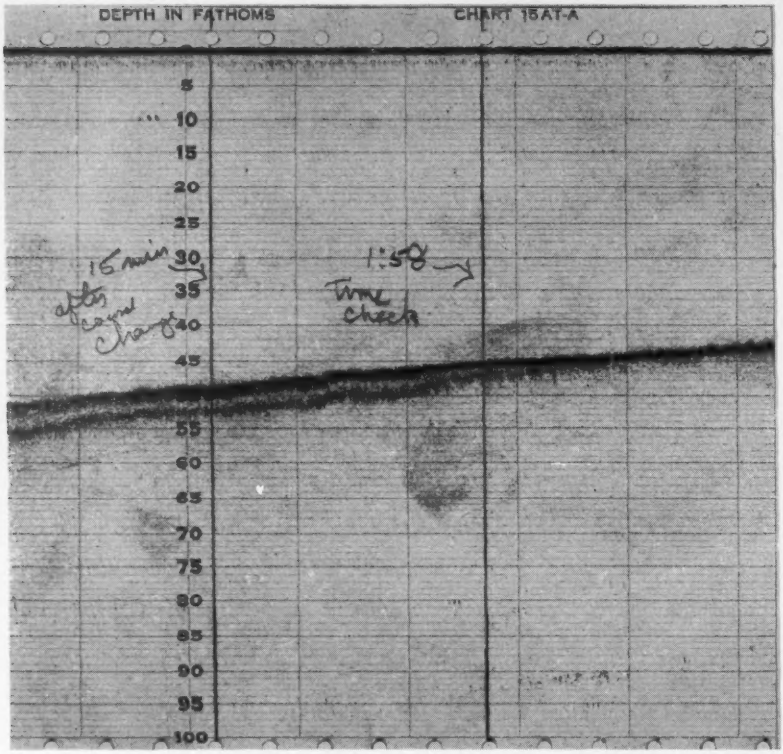

FIG. 7.—Fathogram made under rough water conditions, when seas were short, steep, and confused.

of the red clay; (3) top of till. A faint partial trace, intermediate in position between the second and third traces at the left, may be caused by reflection from the top of the abnormally stiff portion of the red clay zone, which was observed in the core samples taken farther to the right.

ADDITIONAL FATHOGRAMS

Effect of Rough Water

The fathograms presented in all figures except figure 7 were made under especially favorable conditions. The lake surface was in a flat calm condition for most of the profiles, and in a mildly choppy condition for others. Figure 7, however, shows a fathogram made under an unusually severe sea condition. No reliable estimates of wind velocity or wave height are available for the time during which this fathogram was made, but during the storm the wind blew down telephone lines and trees and damaged other property on shore about twenty miles west of the area shown in figure 7, and the vessel, operating at reduced speed, rolled through an arc of about 90 degrees and took "solid" water over its high bow

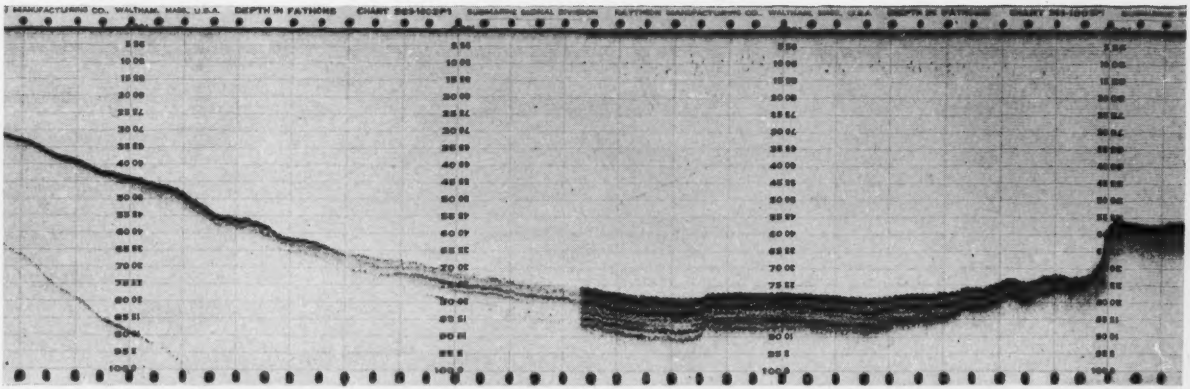

FIG. 8.—The effects of variation in signal strength, depth of water, and softness of bottom are shown. Strength of outgoing signal was constant from left edge to center of figure, whereas the recorded returning signal became weaker. Loss of energy during greater travel time in deeper water, and greater absorption of energy by a soft clay bottom both affect strength of returning signal. Strength of outgoing signal was increased in center of figure, resulting in a greater return of energy and good definition of traces on the fathogram. Typical sand bottom trace in shallow water at left, multiple returns from clay strata in center deep portion, and typical till bottom trace at right.

and its after deck. The seas were short and steep.

No bottom samples were taken in the area represented by figure 7, but the area is on the western side of the southern basin of Lake Michigan and a few core samples taken elsewhere in the basin show a column of several feet of lake clay over till, in the deep water. Fathograms taken on the eastern side of the basin under calm conditions show a double trace changing to a single trace, going toward shallower water. The fathogram of figure 7 appears, therefore, to give approximately as much information as could be expected if it had been made under calm conditions.

Adjustment of Signal Strength

Figure 8 illustrates the effect of signal strength on the quality of fathogram obtained. This fathogram was made from left to right on an easterly (85° true) course from Port Washington, Wisconsin. The signal strength was adjusted to give a strong, clear fathogram trace in the shallow water (at the left end of profile, figure 8); as the vessel travelled eastward in deepening water, the fathogram trace became fainter. Two factors were involved: (1) the path of the sound beam was longer, and more energy was lost by scattering; (2) more energy was absorbed by the soft bottom occurring in the deeper water. At the center of the profile the signal strength was increased (by turning up the power adjustment knob on the fathometer), and this produced a strong, clear fathogram showing several distinct traces. It is interesting to note that one of the intermediate traces below the bottom is much stronger than all others; this is shown most clearly in the portion of the fathogram made just before the signal strength was increased.

No bottom samples were taken along the profile of figure 8, but samples taken along a nearby parallel line with a similar fathogram showed sand bottom in the shallower water at the left, clay bottom in the central deep portion, and till bottom in the shallower water at the right. The meaning of the several (approximately seven) distinct traces in the center of figure 8 is not known, because no long cores were obtained in this area.

Shallow Scattering Zone

Between the depths of five and fifteen fathoms in figure 8, and in several fathograms which are not reproduced in this paper, there appear a number of dots. These presumably are caused by reflections from fish. It is the writer's opinion that these dots appear in the zone of the thermocline (where the temperature and density are changing rapidly from the warmer surface isothermal zone to the colder deep isothermal zone). No water temperature observations were recorded during the period of this cruise, but observations made in the same month (July) in previous years by the writer and by Church (1945) showed a strongly developed stratification of the water, with a temperature difference of as much as 18 degrees C. between the depths of 10 and 20 fathoms, and with the upper limit of the thermocline very sharply developed at depths ranging from 5 to 10 fathoms.

REFERENCES

CHURCH, P. E. (1945) The annual temperature cycle of Lake Michigan; II. Spring warming and summer stationary periods, 1942: Univ. of Chicago Dept. of Meteorology Misc. Repts. No. 18.

MURRAY, H. W. (1947) Topography of the Gulf of Maine: Geol. Soc. America Bull., vol. 58 p. 195.

RUSSELL, R. D. (1950) Applications of sedimentation to naval problems; in: Trask, P. D. (ed.), Applied sedimentation, New York, John Wiley & Sons, Inc., p. 657.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 22, NO. 3, PP. 173–181
FIGS. 1–5, SEPTEMBER, 1952

TRAILS AND ROCKS OBSERVED ON A PLAYA IN DEATH VALLEY NATIONAL MONUMENT, CALIFORNIA

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Death Valley, California

ABSTRACT

Widespread over the surface of a playa located in Inyo County, California are numerous trails each customarily terminating at a rock and/or a mound of dried sediment. These trails, furrow-like in appearance and varying greatly in width and length and in compass direction, give evidence of having been caused by their terminal material having slid over the playa's surface. An explanation proposed by previous writers is that strong gusty winds such as are common in the area are responsible, having caused the rocks and mud curls to move about at a time when the playa was muddy following heavy precipitation.

INTRODUCTION

A playa, called "The Racetrack," which is located in the Cottonwood Mountains of Death Valley National Monument, Inyo County, California has been the subject of considerable lay and professional interest in recent years because of numerous furrow-like trails found on its surface, each customarily terminating at a rock and/or a low mound of dried sediment. The only known previously published report of the occurrence is that of McAllister and Agnew (1948). It gives a brief description of the playa furrows and scrapers stating that no precise measurements were made and proposing that the furrows were caused by the scrapers having been propelled by gusts of winds over the playa surface while it was muddy.

BACKGROUND AND PURPOSE OF THIS REPORT

As a ranger with the National Park Service the author has become familiar with the Racetrack and the trails, but as investigation of the phenomenon as here reported is an outgrowth of personal interest and was undertaken on personal time in a non-official capacity it is not to be construed as necessarily reflecting official Service opinion.

Feeling that circumstances, environmental and/or human, might alter the seemingly natural appearance of the trails and the apparently causative terminal material it was deemed advisable to obtain accurate measurements and representative photographs. Recognizing that increasing interest in the "moving rocks," as the phenomenon is popularly called, is resulting in more than the usual number of visitors to this remote area and that some disturbance has already occurred, recording of the phenomenon seemed urgent.

This report is the result of nearly two years of casual observation and of three days of intensive study, during which time the author and his wife spent at least 20 hours actually on the playa observing and recording. Measurements were very carefully made but emphasis has been placed on presenting a lucid concept of the phenomenon rather than on meticulously precise mensuration. However it is felt that any resultant margin of error would be so slight as to be of negligible significance. Great care was taken throughout the investigation not to alter the natural appearance of the scene.

DESCRIPTION OF THE PLAYA

The Racetrack playa is located at T. 14 S., R. 40 E. on the 1948 Death Valley map NJ 11-11 of the Army Corps of Engineers. It is situated at an elevation of close to 4000 feet above sea level in a

FIG. 1.—A 15-foot loop made by a 36 pound piece of granite (example 9 of table 1). Western shore of playa in background.

valley approximately six or seven miles long and two miles wide with slopes bounding the playa rising rather abruptly and nearby peaks reaching altitudes of 5000 to 6000 feet. The playa measures 2.3 miles from north to south, and 1.5 miles from east to west. Three-tenths of a mile in from the northern rim is an igneous "island" less than one half mile in circumference and possibly reaching a maximum of 50 or 60 feet in height. The area has been and is the scene of considerable small scale mining activity.

METHODS EMPLOYED IN MAKING OBSERVATIONS

A Brunton compass was used in plotting the general course of the rocks and the sediment mounds with readings recorded from a trail's evident inception to its terminus. Trail lengths were measured with a surveyor's chain and widths were taken at the extremities of trail sides with a steel tape. Trail widths and depths are qualified by the term "usual" rather than "mean" because it was felt that a mean measurement would not accurately characterize a trail which, although varying considerably from minimum to maximum, was of one even width for the majority of its length.

Dimensions of the rocks and sediment mounds are careful approximations based upon what seemed to be average depths, widths, and lengths and only data pertaining to the side(s) facing the trail and the bottom of each rock are included as these would appear the most relevant in considering the probable action of a possibly propelling force. In the majority of cases the rocks were oriented with a corner facing the trail and in these cases dimensions of the two intersecting faces are included. Because of the rocks' irregularities computation of volume would necessarily be inaccurate and it

FIG. 2.—Intricate loop of a 786-foot trail made by a 47-pound piece of granite (example 10 of table 1). Compare trail with that shown in figure 1.

was therefore believed that size could best be indicated by weight. To obtain weights spring scales were used. In all cases where rocks weighed over 300 pounds, two scales were used. The rock was freely balanced on a supporting plank, each end of which rested upon a scale, and a cumulative reading was taken with the weight of the supporting plank subtracted. In one case it was necessary to support a rock by the two scales and a block. "Depth" of trails and "distance imbedded" are based upon measurement of maximum depression of the playa surface.

Locations of the examples included in the tables are given in terms of "quarter of playa" which is based upon imaginary north-south, east-west division. "Distance from rim" is based upon odometer readings and refers to the minimum distance to a point of probable origin.

DESCRIPTION OF THE PHENOMENON

Scattered over the surface of the playa are numerous trails which may generally be characterized as "furrows" or "smoothings" in the playa surface. Trails observed ranged in width from two and one half inches to 12 feet and from a negligible depth to a depression of an inch or so. Measured lengths ranged from 34 to 786 feet. Many trails were straight or slightly curving, but many others were zig-zag and at least two made complete loops. The majority ran within 45 degrees of north from their evident inceptions to their termini, although some ran in a definite southerly direction and recordings were made of two highly similar trails which ran at all points of the compass and included complete loops and greater than right angle turns (See figs. 1 and 2). In several instances trails evidently of the same origin were noticed

TABLE 1.—*Types and characteristics of rocks which give evidence of having slid about over the surface of the Racetrack Playa in Death Valley National Monument, California*

(Example numbers correspond to those in Tables 2 and 3)

Example number	Type of Material	Weight, in lbs.	Location		Maximum distance imbedded in playa surface, in inches	Observations
			Quarter of playa	Distance from rim in miles[1]		
1	Limestone	3½	SW	1.4	¾	Oriented with least apparent wind resistance toward trail.
2	Limestone	4½	SW	0.2	¾	Two rocks juxtaposed with N face of limestone ¼″ from S face of granitic rock, as if limestone has pushed granitic rock.
	Granitic rock	2		1.3	1	
3	Granitic rock	1	SW	0.2	½	Oriented with corner toward track. 22′ S was limestone with trail going in opposite direction from this one's.
4	Limestone	60	SW	1.0	2	Oriented with corner toward track. Very rough, irregular shaped rock.
5	Limestone	66	SW	0.8	2¾	15–20 fragments surrounding the rock, especially to S. Playa surface disturbed for 7″ to N of rock.
6	Limestone	603	SE	0.2	2	As evidenced by etching the present S face had previously been imbedded in the playa surface to a depth of 3½″. Oriented with corner toward trail.
7	Limestone	230	SE	0.2	2½	Oriented with corner toward trail.
8	Limestone	320	SE	0.1	2	Oriented with corner toward trail.
9	Granitic rock	36	NE	0.03	½	Playa surface disturbed for 2½″ to N of rock.
10	Granitic rock	47	NE	0.1	1½	Present position only about 200 feet S of previous position.
11	Limestone	142	NE	0.9	1	6 or so fragments to S of rock.
12	Quartz	8	NE	0.05	2	Oriented with corner toward trail. Playa surface pushed up in mound for 2″ to N of rock.

[1] Refers to nearest rim from which rock could likely have originated and not necessarily to closest rim.

in various stages of weathering and apparent age.

At one end of each trail recorded was a rock and/or a low mound of dried sediment and it seems only logical to assume that the trails were caused by the terminal material sliding over the playa surface when it was soft. This is evidenced in part by the rough correspondence of trails' width and depth to the rocks' dimensions, weights, and bottom surfaces. Rocks ranged in size from a cubic inch or so to over three cubic feet and the mud mounds were of widely varying size and shape. In addition to the rocks with trails there were many, particularly small ones within three-tenths of a mile of the western rim, which had no evidence of being associated with trails. In some cases rocks apparently had been nearly contiguous when one moved off. In other instances rocks evidently fairly close together at one time had moved in opposite directions. In general the rocks were oriented with the corner of their most streamlined appearing sides facing the trails. Bottom faces were often very rough with marked projections and depressions.

Rocks observed were of limestone, granitic material, and quartz and ranged in weight from one to 603 pounds. In shape many were completely irregular while others were quite cubical. Several of the limestone rocks showed considerable etching on their bottom surfaces and also in some cases on a surface at present out of the playa mud. It was assumed that this etching was caused by a chemical action of the playa mud on the limestone while the rock was imbedded in the playa. A typical example was a piece of limestone measuring 16×17×24 inches which was embayed for ½ inch on the bottom two or three inches of its imbedded face. This would seem to indicate

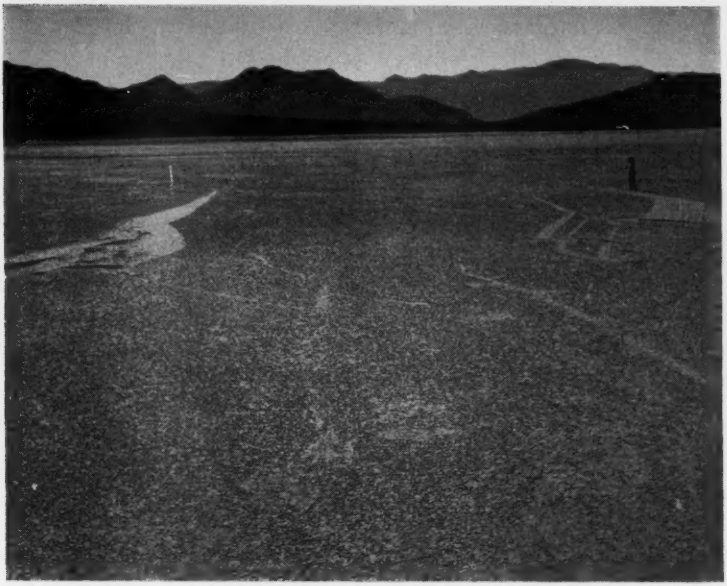

FIG. 3.—Numerous trails made by sediment masses, with example 15S (of table 3) at extreme right side of figure.

that this rock had been on the playa for a considerable time, and more extensive measurements of this etching might be correlated to the solubility of limestone as an index of the minimum length of time the rock had been on the playa. Lying about the bases of a number of the rocks were smaller fragments which apparently had weathered off.

The rocks are widely distributed over the playa with the majority in the southern portion. Within three-tenths of a mile from a limestone bluff bounding the playa on the southeast five large pieces of limestone ranging from 200 to 600 pounds, each with a trail, were observed. Almost one mile out from this apparent point of origin was a 142-pound rock which had a 61-foot trail. Near the western rim and mingled with hundreds of fist-sized granitic rocks were an apparently almost equal number of limestone pieces. In one case a small piece of limestone and a granitic rock appeared to have made a single trail. In another case a mound of sediment was found with a fair sized rock overlapping it laterally, the two having made one trail. The two longest and most erratic trails were in the northeastern portion of the playa and were evidently caused by smooth bottomed pieces of granitic rock.

Emphasis in this report has been placed upon the rocks because they seem the more unusual and interesting, but there were also innumerable trails, highly similar to those described as caused by the rocks, which terminated in mounds of sediment and appeared to have been made by mud curls having slid over the playa (See fig. 3). In many cases small piles of sediment were noticed around the rocks and clearly associated with their movement, the rocks having

TABLE 2.—*Surface characteristics of rocks which give evidence of having slid about over the Racetrack Playa Death Valley National Monument, California*

(Example numbers correspond to those in Tables 1 and 3)

Example number	Side(s) facing trail				Bottom			
	Dimensions		Shape	Nature	Dimensions		Shape	Nature
	Height	Width			Height	Width		
1	1¾	3	Rectangular	Vertical	5	4	Squarish	Flat, irregular
	4	8	Convex Curve	Very sloping				
2 (lmstn)	1½	4	Triangular	Vertical	4	4	Squarish	Flat, rough
(grntc)	3	3	Triangular	Vertical	2	3	Rectangular	Convex, irregular
3	2	2½	Triangular	Vertical	2½	2	Triangular	Flat, smooth
	1¾	2½	Triangular	Vertical				
4	9	10	Triangular	Vertical	10	10	Irregular	Very rough and jagged with 4–5″ depression in center
	9	10	Rectangular	Vertical				
	6	13	Rectangular	Vertical	9	14	Rectangular	Rough with 3½″ projection in center
6	13	27	Rectangular	Vertical	24	18	Rectangular	Flat, rough
	12	18	Irregular	Overhanging				
7	10	11½	Irregular	Vertical	16	12½	Irregular	Flat, rough
	10	12	Rectangular	Sloping				
8	17	21	Triangular	Vertical	19	11½	Oval	Flat, rough
	13	16	Triangular	Vertical				
9	6	7	Rectangular	Slightly overhanging	14	8½	Pentagon	Both convex & concave,smooth
	9	13	Rectangular	Sloping				
10	6	5	Squarish	Sloping	12	9	Irregular	Flat, smooth
11	10	12	Irregular	Overhanging	12	11½	Squarish	Slightly convex smooth
12	3	8	Irregular	Vertical	8	6½	Irregular	Flat, rough
	4	6½	Rectangular	Vertical				

pushed a little pile of sediment ahead of them as they slid over the playa surface.

Until the past month or two of the author's period of acquaintance with the phenomenon the general appearance had changed but slightly, with noticeable alterations being the result of human activity. However within recent weeks heavy rainfall in the Racetrack area resulted in an inundation of the playa and subsequent cursory observations have revealed the obliteration of some formerly noted trails (principally example 6, Table 3), the alteration of some others (especially weathering of the initial 331 feet of example 10, Table 3), and the appearance of several previously unrecorded trails. At the termini of some of these new trails were found twigs while others ended at burro droppings and still others at machine gun cartridges or clips.

POSSIBLE CAUSES

Observers of various degrees of competency have hypothesized differently and with varying degrees of apparent logic. All seem to agree that the trails were caused by movement of the rocks and mud mounds, with forces credited as responsible ranging from "magnetism" and "earth vibrations" to flood waters depositing sediments in the lee of the rocks. Others attribute the trails solely to human activity, especially in the case of the very large rocks which it is opined were moved about in connection with the landing of a mine owner's airplane. The

TABLE 3.—*Characteristics of trails in the surface of the Racetrack Playa, Death Valley National Monument, California*

(Example numbers correspond to the example numbers of Tables 1 and 2, except for numbers followed by the letter "S" which indicate trails evidently caused by sediment whereas numbers 1 through 12 inclusive were associated with rocks. Data relevant to the sediment trails are included here because of their similarity to the rock trails, but they are not included in Tables 1 and 2 because of the disimilarity of terminal material.)

Example number	Usual width, inches	Usual Depth, inches	Total length, in feet	Apparent general course[1]	Observations
1	8	Negligible	34	N 10° W	Dim as if quite weathered. Irregular sides with width varying from minimum of 3″ to maximum of 8″.
2	10	Negligible	70	N	Indistinct at inception. Varies in width from minimum of 3″ to maximum of 20″.
3	2½	½	50	Slight curve, N	Very distinct. Even-sided.
4	10	½	60	N	Ridge in center parallel to sides corresponding in height & position to depression in bottom face of rock.
5	12	Evidenced more by raised mud curls than smoothing or depression	142	W, 14′—N 20° W, 128′	Indistinct as though very weathered. Width varies from minimum of 1i″ to maximum of 29″.
6	48 36	Negligible Negligible	60 90	N 45° W N 35° E	2 very dim, but plainly discernable trails. One evidently made by example 6 and one by example 7 with no way to determine which is which.
7	15	½	220	Slight curve, N 20° E	Very distinct, even-sided.
8	10½	1	86	S 50° W, 77′—S, 9′	Very distinct, even-sided
9	10	1	196	S 76° W, 3.4′—S 25° E, 10.6′—loop 15.5′—curve, N 75° W, 29.3′—straight with jog, N 10° E, 35.5′—curve with jog, N 80° W, 11.7′—N 25° W, 4′—winding curve, N 50° E, 85.5′	Very distinct, even sided. Terminal 85′ showed evidence of rock having stopped in two places.
10	11	1	786	S 50° E, 331′—N 80° W, 10.5′—S 20° W, 13.5′—loop, 18′—W, 22′—straight with 2 short right angle jogs, N 10° W, 36.5′—curve, N 80° W, 354′	Initial 331′ are more weathered than remainder of trail, probably older. Rock evidently had stopped at end of 331′ run, and also had stopped twice in 18′ loop.
11	18	½	61	N 20° W	Very distinct, even-sided.
12	4	¼	125	N 35° E, 25′—gentle winding curve, S 15° E, 100′	Very distinct, even-sided.
13-S	6	¼	61	N 40° E, 12′—E, 23′—N 48° E, 25′	Terminal mud mound 2″ high, 13×13½″. Width of track varies from 3″ to 12″.
14-S	8	Negligible	317	N 45′ E, 33.3′—N 15° E, 12.3′—N 30° W, 37.5′—"S" curve, N 58° E, 57′—curve with right angle jog, N 120.4′—N 50° E, 56.5′	Terminal material consists of mud mound 10×17×3″ with rock 6×5×3″ resting partially upon mud mound.
15-S	varies	¼	84	N with terminal curve to E	Width varies from minimum of 2½″ at inception to 12′ at terminus with low mud ridge clear across.

[1] Reading from inception point toward terminal material. All segments are straight unless otherwise indicated.

FIG. 4.—A 320-pound block of limestone (example 8 of table 1), with an 86-foot trail. Picture shows surface which was imbedded in playa, with a one-foot ruler leaning against it.

author could not observe any pattern to the position of the rocks or the directions they had moved which would logically substantiate such a contention. Furthermore it seems inconceivable that anyone would move scores of rocks of tremendously varying sizes in all directions for the thousands of feet evidenced by the trails. It appears even less likely that a person would shove piles of sediment about in such a manner as to leave trails generally much narrower at their inceptions than at their termini and often with several branching trails leading off from the main one. Trails ending at piles of fresh burro droppings would seem to be further evidence against the movement of terminal material being the result of human activity (See fig. 5).

McAllister and Agnew (1948) have proposed that wind blowing across the playa when it was wet and propelling rocks and sediment are responsible for the trails. Erratic winds of considerable velocity are characteristic throughout the region and during one four-hour period of the author's observation the wind blew alternately from the east, the west, and the south at a conservatively estimated 30 to 40 miles an hour. Accurate precipitation data are unavailable for the area and the official recording for Death Valley National Monument (usually running from 0.5 to 1.5 inches annually), while giving some indication, is probably low because it is based upon data taken at elevations near sea level. As has been mentioned winter rains are occasionally sufficient to flood the playa and summer cloudbursts are a not uncommon occurrence in the region.

Seemingly valid objections have been raised to the wind hypothesis. but it is difficult to find a logical basis for accept-

FIG. 5.—Trails ending at burro dung.

ing on the one hand that wind is responsible for the mud curl trails and for those of small rocks while on the other hand deciding, arbitrarily it would seem, that wind could not propel a rock of such and such a size. It is to be hoped that further investigation by other observers will provide a definite answer. Exhaustive discussion of possible causes is not within the scope of this report whose purpose is to record and not to theorize or speculate.

REFERENCE

McALLISTER, J. F., and AGNEW, A. F. (1948) Playa scrapers and furrows on the Racetrack Playa, Inyo County, California: Geol. Soc. America Bull., vol. 59, p. 1377.

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PLATE 1, FIG. 1, SEPTEMBER, 1952

WIND-BLOWN ROCKS AND TRAILS ON LITTLE BONNIE CLAIRE PLAYA, NYE COUNTY, NEVADA

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ABSTRACT

Controversy regarding the origin of furrows or trails occurring on the surface of the Racetrack Playa in Death Valley National Monument led to the search for evidence of the same phenomenon on other playas. Such evidence was found on Little Bonnie Claire Playa in Nye County, Nevada, first in the form of a few nearly obliterated trails, and later in numerous fresh furrows following a protracted rain and wind storm. The author is of the opinion that the furrows or trails are made in the wet and slippery clay surface of the playa by rocks propelled by the wind.

INTRODUCTION

In 1948, J. F. McAllister and A. F. Agnew of the United States Geological Survey reported on the presence of trails or furrows formed on the surface of the Racetrack Playa in the northwestern part of Death Valley National Monument (McAllister and Agnew, 1948). They attributed the furrows to rocks blown by the wind when the surface of the playa was wet. The present writer visited the Racetrack in the spring of 1950 and observed the penomenon, making measurements of some of the trails and of the rocks that had caused them. Although previously skeptical, the evidence of the many trails with rocks or occasionally mud curls at their ends convinced him of the correctness of the views of McAllister and Agnew.

Since that time a great many people have seen the Racetrack Playa and the furrows, and a large number of hypotheses accounting for their origin have been suggested. These have ranged from ice as the moving agency to tilting of the playa, and from water currents to vibrations. A popular article by Louis G. Kirk, a ranger in Death Valley National Monument (Kirk, 1952a), in a widely-read automobile club publication led to a highly garbled account in a national pictorial magazine (Anonymous, 1952). Kirk has since made careful measurements of lengths of trails and weights of rocks, together with observations on the various types of materials that have caused trails. His later work is presented at another place in the current issue of this journal (Kirk, 1952b).

One of the questions that has consistently been asked when the wind has been suggested as the motivating force of the moving rocks is: "Why are such furrows not reported from other playas?" A casual search of the literature has revealed no other reports, and casual personal observation of a number of other playas had brought to light no similar trails.

However, the sudden wave of general interest in the phenomenon led the present writer to renew his search on other playas in connection with a desert research project for the Office of the Quartermaster General of the United States Army. This was rewarded in January, 1952 by the finding of a few faint trails on a playa in Nevada, and later by finding still more following a wind and rain storm.

LITTLE BONNIE CLAIRE PLAYA

Little Bonnie Claire is a clay playa located in the southwestern portion of Nye County, Nevada, near the eastern boundary of Esmeralda County, and only a few miles north of the northern boundary of Death Valley National Monument. Nevada State Highway 72, connecting roads in the northern part of the

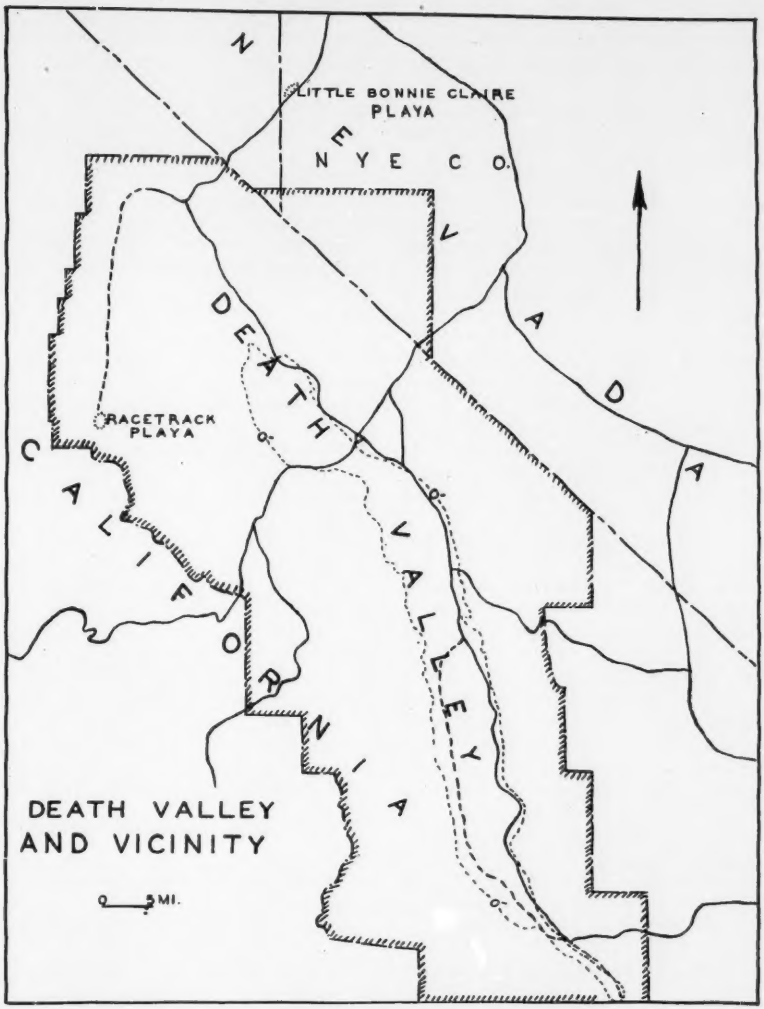

FIG. 1.—Sketch map showing locations of Little Bonnie Claire Playa and Racetrack Playa.

Monument with the Las Vegas-Goldfield road (U. S. Highway 95) skirts the southerly side of the playa. Its elevation is approximately 4000 feet above sea level, which is almost the same as that of the Racetrack Playa (fig. 1).

Rains in the latter part of January, 1952 flooded a part of Little Bonnie

Claire Playa, and in travelling across the dry part just before sundown, the author discovered that the almost horizontal rays of the sun brought out the barely perceptible contrast in relief of a shallow, nearly obliterated trail. This measured 14 feet in length by a few inches in width, and at its end was a small basalt cobble, 6×4×3¾ inches (Plate 1A). Careful search revealed two more trails in the same vicinity, one 20 feet long and the other 2 feet long, and probably more would have been found had not the last of the sun's rays left the surface of the playa. All three trails showed the same characteristic of slumping of the sides as the result of the action of water after having been formed.

In the early part of March, 1952, the writer and his wife were camped in the north end of Death Valley during a wind and rain storm that lasted more than twenty-four hours with the rain almost continuous and the wind in gusts that reached an estimated 30 to 40 miles per hour at times. The latter was in general from a northerly direction. although it occasionally shifted abruptly through a rather wide arc.

On visiting Little Bonnie Claire Playa on the following day, it was found to be entirely covered with a thin sheet of water not more than one-half inch deep. The clay surface was soft and extremely slippery, but beneath the topmost inch the material was quite firm so that a person walking on the playa sank down not more than an inch or two, and even the weight of a jeep made very little impression. However, the slipperiness made it difficult to keep one's feet.

On this occasion, sharp eyesight and perfect conditions of lighting were not necessary to see the trails. All along the southerly and southeasterly portions of the playa, which were the only parts visited, numerous trails were obvious, even though the sky was overcast and visibility was rather poor. Some of the trails were straight, some were gently curved, a few had right angle bends, and a few were serpentinous. They ranged in length from a few inches to more than 100 feet, the longest one measured being 138 feet. All trails terminated in rocks, either basalt or scoria, of various sizes, many of them in the cobble range with dimensions up to 6×4×2 inches. Although larger rocks were present on the surface, they showed no trails, and apparently had not been moved recently. The directions of all the trails were in general the same: from north to south (Plate 1B).

The origin of the trails in this case seems clear to the writer. The steady rain of the previous day (and possibly still earlier rains) had covered the surface of the playa with water, part of which had soaked into the clay on the surface, making it a thin, slippery mud. Gusts of wind, blowing as a rule from north to south, but occasionally veering considerably, pushed against the projecting surfaces of the rocks and drove them southerly. Undoubtedly they did not all move in unison because of different sizes and local surface irregularities, hence the trails are not uniform, some being straight and some being bent, as gusts from varying directions and of varying competencies moved individual

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Explanation of Plate 1

A—Faint, almost obliterated trail of wind-blown rock brought out by nearly horizontal rays of setting sun on dry surface of Little Bonnie Claire Playa. Author's wife marks beginning of trail; basalt cobble is at end. View is a little west of north and was taken from approximately 100 yards out from southerly shore. January 27, 1952.

B—Numerous fresh trails of wind-blown rocks on water-covered surface of Little Bonnie Claire Playa. Paired tracks crossing diagonally from right to left in foreground are of jeep; all others are made by rocks, which are basalt or scoria. View is almost due north and was taken from southern shore of playa. March 8, 1952.

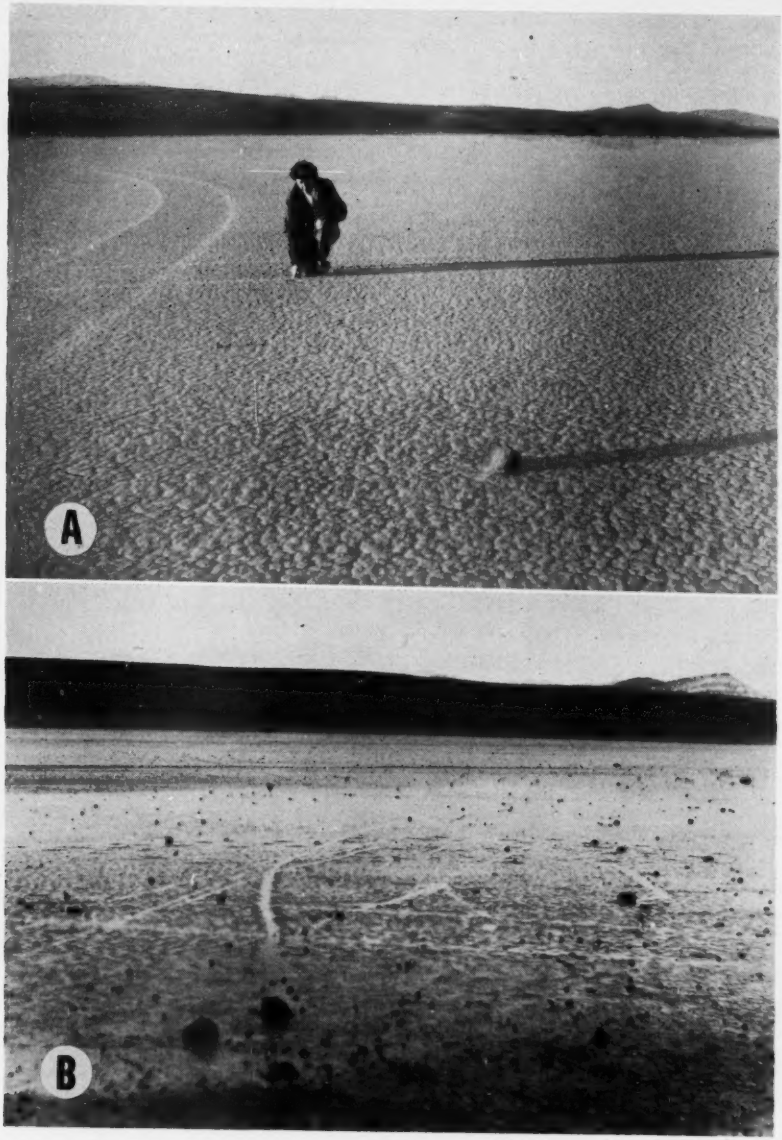

PLATE 1

rocks. The wind was not strong enough to move the larger rocks, but their presence far out from the shores of the playa is difficult to explain excepting as having been blown there during an earlier, more violent storm.

It is these larger rocks that offer the best evidence against ice as a possible transporting agent. At the time the observations were made all the sourrounding mountains were snow covered, with the snow line only slightly above the level of the playa. The water covering the playa was definitely not frozen, although it may have been during the night. If so, and the movement of the sheet of ice had caused the rocks to make the trails, or if there had simply been ice collars frozen around the rocks to act as lifting vanes, as has been suggested as an alternative hypothesis, then the larger rocks should have been moved along with the smaller ones, or there should have been marks of the collars around rocks that did move. The larger rocks showed no trails, however, and there were no marks of possible collars around the smaller rocks. Movement by ice, therefore, seems to be ruled out.

The near-obliteration of the trails first observed on this playa is probably explained by the presence of the sheet of water on the surface at the time the second set of observations was made. Although when examined the new trails were quite sharp and distinct, it is easy to see how waves from even a light breeze rippling the shallow water would soon cause slumping of the sides and even their complete levelling.

CONCLUSIONS

On the basis of the evidence presented, it is the conclusion of the author that the trails or furrows on Little Bonnie Claire Playa have been formed by rocks pushed over the wet and slippery surface by the wind. A further conclusion is that the evidence from this playa supports the original opinion of McAllister and Agnew that similar trails or furrows on the Racetrack Playa were also made by windblown rocks, or other objects propelled by the wind.

Careful work under favorable conditions on other playas should bring to light additional evidence that the wind is responsible for the distribution of rocks over the surfaces of playas in general, thus explaining the occurrence of pebbles, cobbles, and even boulders should such be found in ancient playa sediments in the geologic column.

REFERENCES

Anonymous (1952) The case of the skating stones: Life, vol. 32, no. 10, pp. 53–54.

Kirk, L. G. (1952a) The Racetrack mystery: Westways, vol. 44, no. 2, pp. 24–25.

——— (1952b) Trails and rocks observed on a playa in Death Valley National Monument, California: Jour. Sedimentary Petrology, vol. 22, pp. 173–181.

McAllister, J. F., and Agnew, A. F. (1948) (Abstract) Playa scrapers and furrows on the Racetrack Playa, Inyo County, California: Geol. Soc. America Bull., vol. 59, p. 1377.

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